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STRUCTURAL AND FIELD GEOLOGY

STRUCTURAL AND FIELD GEOLOGY

FOR STUDENTS OF PURE AND APPLIED SCIENCE

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FIFTH EDITION
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PREFACE TO THE FIRST EDITION

THIS Handbook addresses itself, in the first place, to beginners in Field Geology, but I hope it may be found useful also to students who are preparing for professions in which some knowledge of Structural Geology is of practical importance. The amount of geological training demanded varies, doubtless, with the nature of the profession. Mining engineers, for example, must acquire a knowledge of many details which civil engineers, architects, agriculturists, and public health officers can afford to neglect. Nevertheless, if Structural Geology is to be of service to a professional man, it must be studied in a systematic manner. Without an intelligent appreciation of the subject as a whole, it is very hard or well-nigh impossible to gain an adequate working knowledge of any particular part. In the following pages, therefore, the subject is set forth mainly from the point of view of pure science. The student of applied science, however, should have little difficulty in distinguishing between matter of general interest, and that which is of special importance to him, as bearing directly on his professional pursuits. To help in this discrimination two sizes of type have been employed—the smaller type being commonly reserved for details or discussions of import mainly or exclusively to students of pure science. With regard to the matter in larger type, the intelligent student will use his own discretion. To others than mining men, for example, the chapters dealing with ore-formations will not call for much studious consideration. Again, neither civil engineers, public health officers, nor agriculturists may ever be called upon to make a geological survey of any district. Intending professional men will be ill-advised, however, if they do not take the trouble to understand the methods of observation employed in Field Geology, for such knowledge will often be of considerable service in their future careers. To mining and civil engineers, especially, an acquaintance with the methods of geological surveying and map-construction cannot fail to be invaluable, while agriculturists and public health officers ought assuredly to know enough of the subject to understand and interpret a geological map. I may be allowed to add that at the University of Edinburgh we have found no difficulty in teaching Structural and Field Geology to mixed classes of students of pure and applied science. The present Manual may be said to cover the ground gone over in our Summer Course of Geology—a course instituted some twenty years ago to meet the requirements of students desirous of obtaining a fuller knowledge of Practical Geology—more especially field-work—than could be presented in the general systematic course given in winter.

The plates which illustrate this volume have been derived from various sources. A number are reproduced from unpublished photographs taken by Mr R. Lunn for H.M. Geological Survey. Permission to use these was obtained from the Board of Education through the kind offices of Dr Teall, Director of the Geological Survey, and Dr Horne, Assistant Director. No one can be more sensible than myself that these illustrations give an interest to this work which it would not otherwise possess. To my former colleague and lifelong friend, Dr Peach, I am indebted for the coloured section which accompanies one of these plates. Plates X. and XXVI. are reproduced, by the courteous permission of the Controller of H.M. Stationery Office, from published memoirs of the Geological Survey. My friend and former assistant, Dr Flett, now of H.M. Geological Survey, was good enough to supply me with the photograph reproduced on Plate XXXIII., as well as with others which only the limited scope of my book has prevented me using. I am also under many obligations to him for reading some of my proof-sheets, and making various helpful suggestions. To another friend and former pupil, Dr Laurie, I am similarly indebted for the photographs reproduced on Plates XXVII. and LXV., which were taken on one of the excursions of my Summer Class. Mr Francis J. Lewis, of the University of Liverpool, whose investigations into the structure and history of the peat-bogs of Britain promise to be of the greatest interest and importance to botanists and geologists, kindly put at my disposal several characteristic photographs of peat-bogs, from which I selected the illustration that appears in Plate LIV. Unless when otherwise stated, all the other plates are reproductions from photographs of specimens in my own Class-Museum, taken under the superintendence of Dr J. D. Falconer, formerly my assistant and now Director of the Mineral Survey of Northern Nigeria. I may add that many of the illustrations in the text were drawn for me by my son, Mr W. Cranston Geikie.

EDINBURGH, *April* 15, 1905.

PREFACE TO THE FIFTH EDITION

In this new edition of Structural and Field Geology the general scope of the late Professor James Geikie's original work and the method of treatment adopted therein have been in large measure retained. Chapters I. to V., however, which deal with Rock-forming Minerals and Rocks, and Chapter XV., which treats of Alteration and Metamorphism, have been almost completely rewritten. The concluding chapter of the earlier editions, on Geological Structures and Surface Features, has been omitted. In revising the remaining chapters, opportunity has been taken to discard matter which was thought unlikely to be of value to students and to introduce many of the new ideas and terms in tectonic and economic geology which have gained acceptance in recent years.

Twenty-five new plates and four new text figures have been introduced, and nearly all the text figures and most of the plates of the earlier editions are retained. We are greatly indebted to Dr W. Q. Kennedy, who has supplied the maps (Fig. 56) illustrating the transcurrent faulting along the line of the Great Glen, and to Dr J. E. Richey, who helped generously in the preparation of the diagrams (Figs. 84 and 85) showing ring-dykes and cone-sheets. Fig. 79 is taken from Dr Richey's Monograph on "The Dykes of Scotland," and is reproduced by permission of the Council of the Edinburgh Geological Society, to whom we are also under obligation for the loan of the zinc-etching. The Geological Survey of Scotland photographs used in Plates XVIII., L., LVII. and LXVII. are Crown copyright and are reproduced by permission of the Controller of H.M. Stationery Office. Plates XLI. and LVI. have been selected from the admirable collection of photographs of Scottish scenery taken by Mr Robert M. Adam of the Royal Botanic Garden, Edinburgh. Our cordial thanks are due to our friend Mr A. G. Stenhouse for the photographs reproduced on Plates XLVIII. and LXIV., and we are indebted to him also for his kindness in reading the proofs.

ROBERT CAMPBELL.
R. M. CRAIG.

EDINBURGH, *January* 8, 1940.

CONTENTS

CHAPTER I

ROCK-FORMING MINERALS

PAGE

Oxides :—Quartz and its varieties ; Chalcedony ; Opal ; Hæmatite ; Limonite ; Spinel Group (Spinel, Chromite, Magnetite) ; Ilmenite ; Rutile ; Corundum ; Pyrolusite, Psilomelane, and Wad. Silicates :—Feldspar Group ; Feldspathoid Group . 1-15

CHAPTER II

ROCK-FORMING MINERALS—*continued*

Silicates :—Mica Group ; Amphibole Group ; Pyroxene Group ; Olivine Group ; Chlorite Group ; Talc Group ; Glauconite Group ; Epidote Group ; Garnet Group ; Zircon Group ; Titanite ; Tourmaline Group ; Andalusite Group ; Cordierite ; Zeolite Group ; Kaolinite Group. Haloids :—Fluorite and Rock-Salt. Sulphides :—Pyrite, Pyrrhotite, and Marcasite. Carbonates :—Calcite, Aragonite, Dolomite, and Siderite. Sulphates :—Anhydrite, Gypsum, and Barytes. Phosphates :—Apatite, etc. Elements :—Graphite 16-32

CHAPTER III

ROCKS

Classification :—Crystalline Igneous Rocks — their General Characters. Chief Minerals of Igneous Rocks. Primary and Secondary Minerals. Groups of Igneous Rocks :—Feldspathic Rocks with abundant Quartz ; Feldspathic Rocks, free from or poor in Quartz or Feldspathoids ; Feldspathic Rocks with abundant Feldspathoids ; Feldspathoidal Rocks, free from or poor in Feldspars ; Rocks without Essential Feldspars or Feldspathoids. Pyroclastic Rocks 33-60

CHAPTER IV

ROCKS—*continued*

PAGE

Classification of Derivative Rocks:—I. Mechanically formed Rocks, including Subaërial and Æolian, Sedimentary, and Glacial Rocks (Soil and Subsoil, Rock-rubble, Rain-wash, etc., Blown Sand and Dust, Laterite, Terra Rossa, Conglomerate, Grit and Sandstone, Greywacké, Clay, Till, etc.). II. Chemically formed Rocks (Stalactites and Stalagmites, Tufa, Dolomitic Limestone, Rock-Salt, Gypsum, Siliceous Sinter, Flint, etc., Ironstones). III. Organically derived Rocks (Limestone, Siliceous Rocks, Carbonaceous Rocks, Bituminous Rocks, Phosphatic Rocks) 61-82

CHAPTER V

ROCKS—*continued*

Metamorphic Rocks, their General Characters. A—Schistose and Foliated Rocks—Mica-schist, Schistose Grits, Chlorite-schist, Talc-schist, Hornblende-schist, Gneiss. B—Granoblastic Rocks—Quartzite, Granulite, Marble, Hornfels. C—Cataclastic Rocks—their General Characters. Mylonites; Friction-breccias 83-91

CHAPTER VI

FOSSILS

Modes of Preservation of Organic Remains. Kinds of Rock in which Fossils occur. Fossils chiefly of Marine Origin. Importance of Fossils in Geological Investigations. Climatic and Geographical Conditions and Terrestrial Movements deduced from Fossils. Geological Chronology and Fossils 92-104

CHAPTER VII

STRATIFICATION AND THE FORMATION OF ROCK-BEDS

Consolidation of Incoherent Accumulations. Lamination and Stratification. Extent and Termination of Beds. Contemporaneous Erosion. Diagonal Lamination and Stratification. Grouping of Strata. Contemporaneity of Strongly Contrasted Strata. Surface Markings 105-120

CHAPTER VIII

CONCRETIONARY AND SECRETIONARY STRUCTURES

PAGE
Siliceous Concretions—Flint, Chert, Menilite. Calcareous and Ferruginous Concretions — Septaria, Composite Nodules, Rattle-stones, Fairy-stones, Kankar, etc. Clay-ironstone Nodules, Pyrite, Marcasite, Gypsum, Dendrites. Concretionary Sandstones, Argillaceous Rocks, and Limestones. Concretionary Tuffs. Concretions in Crystalline Igneous Rocks. Secretionary Structures—Amygdales, Geodes, Drusy Cavities 121-126

CHAPTER IX

INCLINATION AND CURVATURE OF STRATA

Dip—Apparent and True. Terminal Curvature. Outcrop influenced by Angle of Dip and Form of Ground. Strike. Curvature of Strata—Monoclinal Folds, Quaquaversal and Centroclinal Folds, Normal or Vertical Folds, Inclined Folds, Inversion, Recumbent Folds, Fan-shaped Structure, Contorted Strata 127-143

CHAPTER X

JOINTS

Joints, Close and Gaping. Joints in Bedded Rocks—Master-joints, Dip- and Strike-Joints. Joints in Igneous Rocks—in Granitoid Rocks, Prismatic Joints. Joints in Schistose Rocks. Slickensides. Origin of Joints—Contraction, Expansion, Crustal Movements 144-153

CHAPTER XI

FAULTS OR DISLOCATIONS

Normal Faults. Dip-faults and Strike-faults—their Effect upon Outcrops. Oblique Faults. Systems of Faults. Step-faults. Trough- and Ridge-faults. Shifting of Faults. Reversed Faults. Transcurrent Faults. Origin of Faults . . 154-179

CHAPTER XII

STRUCTURES RESULTING FROM DENUDATION

Outliers and Inliers. Unconformity. Overlap . . . 180-187

CHAPTER XIII

ERUPTIVE ROCKS: MODE OF THEIR OCCURRENCE

PAGE

Intrusive Eruptive Rocks. Plutonic or Abyssal and Hypabyssal Rocks—their General Petrographical Characters. Subjacent Masses—Batholiths, Stocks, Bosses. Mode of Emplacement of Batholiths. Injected Masses—Laccoliths, Sills, Lopoliths, Phacoliths; Dykes and Veins; Ring-dykes and Cone-sheets 188-207

CHAPTER XIV

ERUPTIVE ROCKS: MODE OF THEIR OCCURRENCE—*continued*

Necks or Pipes of Eruption—their General Phenomena. Effusive Eruptive Rocks—Crystalline Effusive Rocks and Pyroclastic or Fragmental Effusive Rocks 208-216

CHAPTER XV

ALTERATION AND METAMORPHISM

Rock-changes induced by Epigene Action. Deep-seated Alteration or Metamorphism. Degrees of Metamorphism. Thermal or Contact Metamorphism. Dynamic Metamorphism. Dynamothermal Metamorphism. Plutonic Metamorphism . . 217-231

CHAPTER XVI

ORE-FORMATIONS

Syngenetic Ore-Formations—Native Metals and Ores in Igneous Rocks; Ores in Bedded Rocks (Chemical Precipitates, Clastic Ores, Ores in Schists). Epigenetic Ore-Formations—Fissure Veins or Lodes; Nature of Fissures; Width and Extent of Lodes; Simple and Complex Lodes; Transverse and Coincident Lodes; Systems of Lodes; Branching and Intersection of Lodes; Heaving of Lodes; Contents of Fissure Veins; Structure of Fissure Veins; Outcrop of Lodes; Gossans; Association of Ores in Lodes; Succession of Minerals in Lodes; Walls of Lodes; Stockworks; General Remarks on Fissure Veins 232-254

CHAPTER XVII

ORE-FORMATIONS—*continued*

Bedded Veins or Quasi-bedded Ore-Formations. Irregular Ore-Formations—Masses occupying Cavities; Metasomatic Replacement; Impregnations; Disseminations; Contact Ore-Formations. Origin of Ore Deposits 255-267

CHAPTER XVIII

GEOLOGICAL SURVEYING

PAGE

Geological Surveying. Field Equipment. Topographical Maps. Data to be Mapped. Various Scales of Maps. Signs and Symbols. Tracing of Exposed Outcrops. Tracing of Concealed Outcrops—Evidence supplied by Soils and Subsoils, by Vegetation, by Form of Surface, by Springs, by Index-beds, by Alluvial Detritus. Carrying Outcrops across Superficial Formations 268-284

CHAPTER XIX

GEOLOGICAL SURVEYING—*continued*

Forms of Outcrop. Measurement of Thickness of Strata. Thickening and Thinning of Strata. Unconformity. Overlap. Normal Faults. Reversed Faults. Eruptive Rocks and Contact Metamorphism. Regional Metamorphism . 285-298

CHAPTER XX

GEOLOGICAL SURVEYING—*continued*

Mapping of Unconsolidated Tertiary Deposits, and of Glacial and Fluvio-glacial Accumulations—Boulder-clay; *Roches Moutonnées*; Terminal Moraines, etc. Raised Beaches. Lacustrine and Fluviatile Deposits. Peat 299-311

CHAPTER XXI

GEOLOGICAL MAPS AND SECTIONS

Geological Maps and Explanatory Memoirs. Geological Sections —Horizontal Sections should show both the Form of the Ground and the Geological Structure; Direction in which such Sections should be drawn; Method of Plotting a Section on a True Scale. Vertical Sections. Surveying by Aerial Photography 312-320

CHAPTER XXII

ECONOMIC ASPECTS OF GEOLOGICAL STRUCTURE

The Search for Coal—Conditions under which Coal occurs. Trial Borings. The Search for Ores—General Considerations which should guide the Prospector; Nature of the Evidence. Prospecting by Geophysical Methods. Geological Structure and Engineering Operations—Excavations, Tunnels, Foundations 321-334

CHAPTER XXIII

ECONOMIC ASPECTS OF GEOLOGICAL STRUCTURE—*continued*

PAGE

Water-supply. Lakes and Impounded Streams. Reservoirs. Supply from Rivers. Underground Water—the Water-table; Natural Springs as illustrating the Course followed by Subterranean Water; Shallow and Deep-seated Springs. Common Wells and Driven Wells. Artesian Wells. Considerations to be kept in view in the Search for an Artesian Water-supply. Drainage 335-353

CHAPTER XXIV

SOILS AND SUBSOILS

Agents of Disintegration—Insolation and Deflation; Rain; Frost; Life. Weathering of Rocks. The Soil-cap. Classification of Soils:—I. Bed-rock Soils, their Varied Character; Soils derived from Igneous, Metamorphic, and Derivative Rocks. II. Drift Soils; Glacial, Alluvial, and Æolian Soils. Climate and Soil Formation. Soil Deterioration and Soil Erosion 354-378

APPENDICES

APPENDIX

A.—TABLE OF BRITISH FOSSILIFEROUS STRATA 379

B.—MOHS' SCALE OF HARDNESS 380

C.—COMPASS AND CLINOMETER 381

INDEX 383

ILLUSTRATIONS

FULL-PAGE PLATES

PLATE FACE PAGE

I. Agate. Rock-crystal with Rutile. Garnet 1

II. Photo-micrographs of Leucite, Nepheline, Quartz and Apatite 5

III. Photo-micrographs of Sanidine, Plagioclase, Microcline and Microcline-perthite 12

IV. Photo-micrographs of Hornblende, Augite, Biotite and Olivine 16

V. Serpentine and Chrysotile 23

VI. Photo-micrographs of Sphene, Garnet, Sillimanite, Chiastolite and Cordierite 26

VII. Photo-micrographs of Structures in Glassy Rocks . 35

VIII. Spherulitic and Banded Obsidian 36

IX. Graphic Granite. Druse in Granite 38

X. Photo-micrographs of Granite, Luxulyanite, Granophyre and Quartz-porphyry 43

XI. Porphyritic Structure. Granitoid Structure . . 45

XII. Photo-micrographs of Syenite, Trachyte, Hornblende-andesite, Hypersthene-andesite 46

XIII. Orbicular Gabbro. Tuff 49

XIV. Photo-micrographs of Gabbro, Troctolite, Dolerite and Basalt 53

XV. Scoriæ or Volcanic Cinders 55

XVI. Photo-micrographs of Peridotite, Serpentine, and Tuff . 58

XVII. Volcanic Bombs 60

XVIII. Sand-hills, Culbin, Morayshire 64

XIX. Boulder-clay. Brownhead, South Arran . . . 69

XX. Stalagmite, Gibraltar 70

XXI. Photo-micrographs of Estuarine Sandstone, Æolian Sandstone, Chalk, and Radiolarian Chert . . . 75

XXII. Crinoidal Limestone. Shelly Limestone . . . 76

XXIII. Spotted Slate. Gneiss 85

PLATE FACE PAGE
XXIV. Gneiss with Phacoids 87
XXV. Photo-micrographs of Gneiss, Hornblende-schist, Granulite, and Hornfels 90
XXVI. Current Bedding in Sandstone, Arran . . . 92
XXVII. Rill-marks and Ripple-marks 117
XXVIII. Casts of Sun-cracks (Sandstone). Modern Rain-prints. Fossil Rain-prints 119
XXIX. Septarian Nodule. Ferruginous Concretions . . 122
XXX. Dendritic Markings 124
XXXI. Anticlinal Fold, Liddel Water 129
XXXII. Contorted Schists, etc.—Ben Vrackie 135
XXXIII. Contorted Limestones, Alps and Glen Tilt . . . 138
XXXIV. Flagstones traversed by two sets of Joints, Buchollie Castle, Caithness 144
XXXV. Columnar Basalt, near Kinghorn, Fife . . . 149
XXXVI. Slickensides 150
XXXVII. Joints in Ripple-marked Sandstone, Fifeshire Coast 152-153
XXXVIII. Tabular Joints in Granite, Goatfell, Arran . . 152-153
XXXIX. Curved Joints in Felsite, Arran 155
XL. Fault-rock, Dalnacardoch, Perthshire 156
XLI. Great Glen Fault, Loch Oich to Loch Ness . . . 165
XLII. Meall a Ghiubhais, Ben Eay, Ross-shire, showing Thrust-plane 166
XLIII. Asymmetrical Fold, Santis Mountains 171
XLIV. Section of Sgurr Ruadh (*coloured*) . . . 172-173
XLV. Sgurr Ruadh, showing Thrust-planes . . 172-173
XLVI. The Mythen and Rote Fluh 178
XLVII. Archæan Gneiss with Outliers of Torridon Sandstone, Sutherland 183
XLVIII. Unconformities at Siccar Point, Berwickshire, and Polneul Burn, Sanquhar 186
XLIX. Junction of Granite with Gneiss. Vein of Granite . 191
L. Sill, Drumadoon, Arran 193
LI. Dolerite Sill, cutting Sedimentary Strata, Kinghorn, Fife 197
LII. Traprain Law, East Lothian—a Laccolith . . . 198
LIII. Basalt Dyke, Kilbride Bennan, Arran 203
LIV. Basalt Veins, Kingscross Point, Arran 204

PLATE FACE PAGE
LV. Dyke of "White Trap," St Monans, Fife . . . 208
LVI. Tertiary Lavas, Beinn Edra, Trotternish, Skye . . 215
LVII. North Berwick Law 218
LVIII. Strain-slip Cleavage in Phyllite. Schistose Conglomerate. 225
LIX. Structure of Lodes 240
LX. Signs used on Maps of H.M. Geological Survey . . 275
LXI. Ben Arkle, Sutherland. Archæan Gneiss overlaid unconformably by white Cambrian Quartzite . . 286
LXII. Glaciated Surfaces, Achnashellach, Ross-shire . . 289
LXIII. Striated Surface, Kilchiaran, Islay 304
LXIV. Raised Beaches, Kincraig Hill, Elie 309
LXV. Skeleton Geological Map with Field Data (*coloured*) 312-313
LXVI. Completed Geological Map with Section (*coloured*) 312-313
LXVII. Hummocky Moraines, Lochan an Iasgaich, Ross-shire . 316
LXVIII. Joints in Dolomite, Cinque Torri, Tyrol . . . 357
LXIX. Crest of Goatfell, Arran—Granite breaking up under Action of Weather 364

ILLUSTRATIONS IN TEXT

FIG. PAGE

1. Crystal of Quartz 3
2. Crystal of Rutile 9
3. Crystal of Orthoclase: Carlsbad Twin 11
4. Stratification and Lamination 109
5. Shales and Limestone 110
6. Distribution of Marine Accumulations 112
7. Thinning-out of Strata 112
8. Contemporaneous Erosion 113
9. Dip and Strike of Strata 128
10. Apparent and True Dip 129
11. Terminal Curvature in Steeply-inclined Strata . . . 129
12. Terminal Curvature in Horizontal and Inclined Strata . . 130
13. Outcrops concealed under Boulder-clay 130
14. Outcrops concealed under Overlying Strata 130
15. Width of an Outcrop affected by Angle of Dip . . . 131
16. Width of Outcrop affected by Form of Ground . . . 132
17. Outcrop and Strike 132
18. Strata striking at each other 133
19. Monoclinal Flexure 134
20. Monoclinal Fold showing Thinning of Beds in the Fold . . 134
21. Quaquaversal Fold 135
22. Centroclinal Fold 135
23. Normal Folds 135
24. Normal or Vertical Folds 136
25. Model of Denuded Synclinal and Anticlinal Folds . . . 136
26. Folds with Inclined Axial Planes 137
27. Much Compressed Inclined Folds 138
28. Inclined Flexures: Overfolds 138
29. Isoclinal Folds 139
30. Isoclinal Folds, much Denuded 139
31. Recumbent Fold 139
32. Fan-shaped Structure 140
33. Diagram of an Anticlinorium 140
34. Diagram of a Synclinorium 141

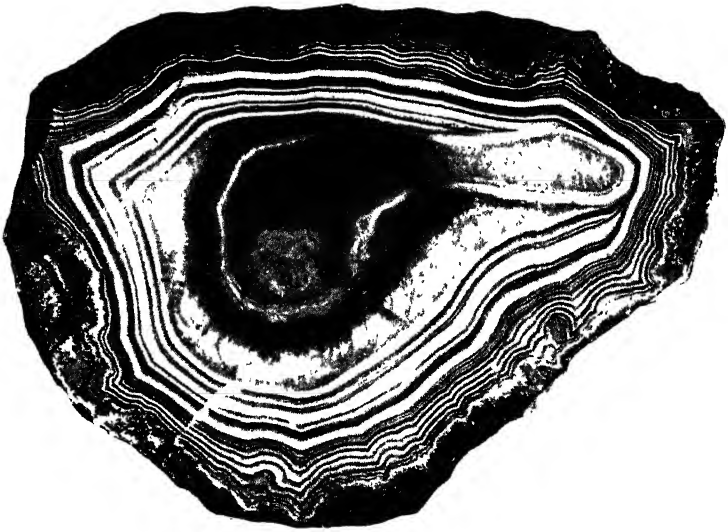
FIG. PAGE
35. Simple Type of Mountain Structure 141
36. " " 142
37. Contorted Folds 142
38. Normal Faults in Horizontal Strata 155
39. Normal Fault in Inclined Strata 155
40. Normal Fault, not accompanied by Distortion 157
41. Normal Fault, accompanied by Distortion 157
42. Effect produced on Outcrops by Dip-Fault 159
43. Effect produced on Outcrops by Dip-Fault traversing Synclinal Strata 159
44. Effect produced on Outcrops by Dip-fault traversing Anticlinal Strata 160
45. Effect produced on Outcrops by Strike-fault with Downthrow in the Direction of Dip 160
46. Effect produced on Outcrops by Strike-fault with Downthrow against the Dip 162
47. Effect produced on Outcrops by Strike-fault with a Diminishing Downthrow 162
48. Effect produced on Outcrops by Oblique Faults 163
49. Complex Fault 165
50. Step-faults 165
51. Step-faults hading against the Dip 165
52. Trough-faults and Ridge-faults 166
53. Shifting of one Fault by another 167
54. Intersecting Faults 167
55. Reversed Faults 168
56. Great Glen Fault 170
57. Parallel Faults with Distorted Strata between 172
58. Monoclinal Flexure passing into a Normal Strike-fault, viewed in opposite directions 172
59. Reversed Fault replacing Monoclinal Flexure 173
60. Origin of Reversed Faults in highly Folded Rocks . . . 173
61. Faulted Recumbent Fold 174
62. Schematic Sections of the Glarner Region 175
63. Translated Rock-sheets 176
64. Escarpment and Outlier 181
65. Outliers and Inliers in Conformable and Unconformable Strata 181
66. Summit of an Anticline forming an Inlier 182

FIG. PAGE
67. Inlier resulting from Faulting 182
68. Marked Unconformity in Horizontal Strata 183
69. Incidental Evidence of Unconformity in Horizontal Strata . 183
70. Strong Unconformity 184
71. Two Unconformities 185
72. Unconformity and Overlap 186
73. Diagrammatic Section across a Batholith 190
74. Granite Sill or Sheet 194
75. Granite Batholith sending out Sills 194
76. Laccolith 195
77. Sill or Intrusive Sheet. 196
78. Diagram of a Sill, showing its former extension as a Laccolith 198
79. Trends of Tertiary Dykes 200
80. Prismatic Jointing in a Dyke 202
81. Complex Prismatic Jointing in a Dyke 202
82. Dyke, showing Usual Position of Vapour Pores and Vesicles . 203
83. Veins proceeding from a Mass of Granite 203
84. Ideal Ring Complex of Ring-dykes and Cone-sheets . . 205
85. Map of Ring-dykes and Cone-sheets, Ardnamurchan . . 206
86. Neck occupied by Crystalline Igneous Rock 210
87. Neck occupied by Agglomerate 210
88. Neck occupied by Agglomerate and Crystalline Igneous Rock. 210
89. Cone of Agglomerate, and Neck of Crystalline Igneous Rock 212
90. Effusive Igneous Rocks 214
91. Plan of a Batholith with Aureole of Metamorphosed Rocks . 220
92. Section at Blaafjeld, Norway 234
93. Sketch-Plan of Meinkjär, Norway 235
94. Seams and Nodules of Clay-ironstone in Carboniferous Shales 236
95. Section of Auriferous Lead (or Placer) on the Lower Murray, near Corowa 236
96. Fissure-vein or Lode 239
97. Simple Lode showing Massive Structure 241
98. Complex Lode 241
99. Lode dividing and branching in Igneous Rock (Plan) . . 241
100. Transverse Lode 242
101. Coincident Lode 242

FIG. PAGE
102. Lode dividing and re-uniting 243
103. Lodes converging and diverging 243
104. Lodes converging and intersecting 244
105. Lodes intersecting at Right Angles without Displacement (Plan) 244
106. Contemporaneous Cross-veins (Plan) 245
107. Heaving of one Vein by another 245
108. Lamellated Lode 247
109. Brecciated Lode. 247
110. Reopening and Refilling of Veins 248
111. Stockwork. 253
112. Diagram-section to show the General Structure of "Saddle-Reefs" 256
113. Diagram to show Mode of Occurrence of Bohnerz . . . 257
114. Veins in Limestone 258
115. Metasomatic Replacement of Limestone by Hæmatite . . 259
116. Reversed Fault in the Gold-bearing Rocks at Johannesburg . 261
117. Section. Contact Ore-formation of Goroblagodat (Ural Mountains) 263
118. Travelling of Soil and Subsoil 278
119. Surface Features in Gently-folded Sandstones . . . 280
120. Form of Ground influenced by Geological Structure . . 281
121. Concealed Outcrops 284
122. Measurement of Inclined Strata 286
123. Ground-Plan of an Unconformity. 288
124. Ground-Plan of Unconformity and Overlap 288
125. Escarpment and Dip-slope 290
126. Inclined "Soft" Rocks overlying "Hard" Rocks . . 290
127. Faulted Strata striking at each other 291
128. Ground-Plan of Neck 294
129. Cleavage and Bedding 296
130. Concealment of Outcrop by Surface Wash 300
131. Coarse Gravel and Shingle, showing Imbricated Structure . 307
132. Section on a True Scale—the Horizontal and Vertical Scales being the same 316
133. Section across same area as in Fig. 131—the Vertical being three times greater than the Horizontal Scale . . . 316
134. Diagram-section 318

FIG. PAGE
135. Tunnel through Synclinal Strata 332
136. Heaping-up of Water in Superficial Deposits. . . . 339
137. Drainage in Horizontal Strata 339
138. Drainage in Synclinal Strata 340
139. Drainage in Anticlinal Strata 340
140. Drainage in Massive Igneous Rock 342
141. Heaping-up of Water in Igneous Rock 342
142. Interception of Underground Drainage by Intrusive Rock . 343
143. Interception of Underground Drainage by Dyke . . . 343
144. Interception of Underground Drainage by Fault . . . 344
145. Heaping-up of Water in Horizontal Strata 344
146. Artesian Wells 348
147. Water-bearing Beds wedging out downwards. . . . 349

PLATE I



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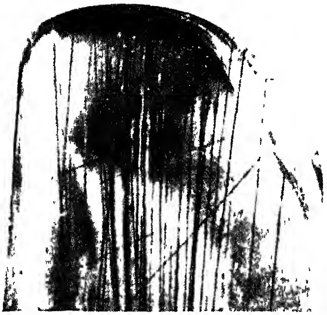

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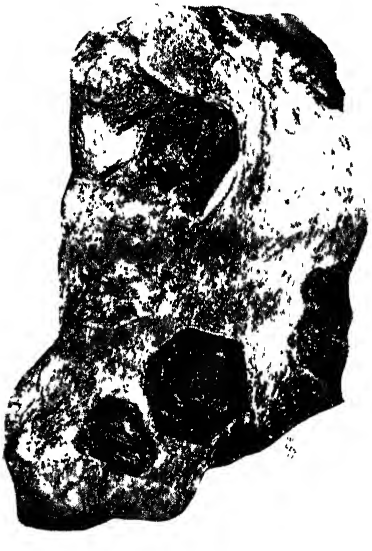

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1. Section of Agate from an amygdaloidal cavity. Nearly natural size.
2. Rock-crystal, enclosing needle-like Rutile.
3. Garnets in Mica-schist.

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STRUCTURAL AND FIELD GEOLOGY

CHAPTER I

ROCK-FORMING MINERALS

Oxides—Quartz and its varieties; Chalcedony; Opal; Hæmatite; Limonite; Spinel Group (Spinel, Chromite, Magnetite); Ilmenite; Rutile; Corundum; Pyrolusite, Psilomelane, and Wad. Silicates—Feldspar Group; Feldspathoid Group.

BEFORE the phenomena presented by the framework of the earth's crust can be fully appreciated, one ought to have some knowledge of rocks and their various constituents. This is all-important for the student who is specialising in geology. For others who wish merely to obtain such aid in their several occupations as this science can supply, a more moderate acquaintance with minerals and rocks than the geologist requires may suffice, and it is for this class of students more especially that the following descriptions have been written. In these introductory chapters, therefore, special attention is paid to macroscopic or megascopic characters—those, namely, which may be observed in hand specimens, with or without the help of a pocket-lens. As it is hoped, however, that some readers may be sufficiently interested to wish to know more, a few notes in smaller type have been added, giving further details and describing characters which can only be studied in thin slices under the microscope. It is quite a mistake to suppose that any great knowledge of mineralogy is required to enable one to determine the essential ingredients of a fine-grained rock in this way. With ordinary application one may in a short time acquire sufficient skill to diagnose microscopically all the more commonly occurring rocks—those, namely, which are likely to come under the notice of architects, civil engineers, agriculturists, and others.

The rock-forming minerals are not a numerous class, and only a few are of pre-eminent importance. For example, the essential mineral constituents of the most abundant and widely distributed igneous rocks may be counted on the fingers. The components of common schistose rocks, and of the great class of derivative rocks, are equally few in number.

For determination of minerals in hand specimens the student should make himself familiar with the most commonly occurring geometrical forms and the combinations of these found in crystals belonging to the various crystal systems. In the *Cubic* (*Isometric*) *System* the forms of most frequent occurrence are the cube, the regular octahedron, the rhombic dodecahedron and the icositetrahedron; in the *Hexagonal* and *Trigonal Systems* hexagonal prisms, usually accompanied by hexagonal " pyramids " and " bipyramids " are characteristic, the latter including such forms as rhombohedra and scalenohedra which are not true bipyramids; crystals of the *Tetragonal System* can usually be recognised easily from the dominance of square prisms and the corresponding pyramidal forms, and those of the *Orthorhombic System* by the characteristic rhombic prisms with accompanying pyramids or bipyramids; in *Monoclinic* crystals four-sided " oblique " prisms are found, associated with various pinacoids, forms each consisting of two parallel faces, while in normal *Triclinic* crystals all the forms are pinacoids.

A preliminary study should be made also of the common physical characters of minerals, particularly those depending on light and cohesion. Of the characters depending on light the most useful are colour, streak (the colour of the powdered mineral), degree of transparency, and lustre (the kind of appearance in reflected light). Properties dependent on cohesion include hardness, cleavage (the property of splitting more or less easily along one or more planes giving smooth, lustrous surfaces—the planes are always parallel to the faces of commonly occurring crystal faces), fracture, tenacity, elasticity, flexibility, etc. Specific gravity is a most useful property, and such characters as taste, odour, and feel, and varying degrees of magnetism are sometimes of diagnostic value.

When the student has familiarised himself with the macroscopic characters of the common rock-forming minerals and is able to determine some twenty minerals under the microscope, he should have little difficulty in diagnosing most of the fine-grained rocks that he is likely to meet with. Slight though this knowledge may be, it will yet enable him to appreciate what petrographers have to say as to the genesis of crystalline igneous and schistose rocks, and will undoubtedly aid him in his own field-observations.

For convenience of description, the common rock-forming minerals have been grouped under the following heads: Oxides, Silicates, Haloids, Sulphides, Carbonates, Sulphates, Phosphates, and Elements. As the minerals included under these several heads are of very unequal importance, the descriptions of the less significant species are given in small type.

Rock-Forming Minerals

I. OXIDES

By far the most important rock-forming oxide is silica, next to which come various oxides of iron. The other oxides here described are of less frequent occurrence—some two or three being hardly entitled to rank as true rock-formers.

Quartz is chemically pure silica (SiO_2). It is harder than any other common rock-former, being 7 in the scale of hardness.* The minerals which are much harder than quartz play a very subordinate part in rocks, the only species that need be mentioned here being spinel and corundum. Quartz has a specific gravity of 2·65, and, when it assumes a crystalline form, appears most frequently as hexagonal prisms terminated by corresponding "pyramids" (see Fig. 1). It breaks with a shell-like (conchoidal) fracture. In its purest form the mineral is water-clear and has a vitreous lustre. It is insoluble either in hydrochloric, sulphuric, or nitric acid.

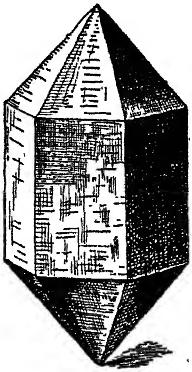

FIG. 1.—CRYSTAL OF QUARTZ.
A combination of hexagonal prism and hexagonal "bi-pyramid."

Quartz occurs in several ways:—1. Frequently it is a product of igneous fusion, being met with as an original constituent of many kinds of eruptive rock, such as granite, quartz-porphyry, rhyolite, etc. 2. It is a not less important ingredient of many schistose rocks, such as gneiss, mica-schist, etc., and is thus the result of metamorphic action—the nature of which will be considered in a subsequent chapter. 3. Quartz occurs also as a deposition from aqueous solution, and as such has a very wide distribution. Silica deposited in this way is derived chiefly from the chemical decomposition of rock-forming silicates. Such solutions, percolating through the rocks of the earth's crust, have brought about manifold changes. Frequently, for example, we find quartz replacing the original constituents of rocks. Again, many more or less loosely aggregated rocks have been permeated by siliceous solutions and converted into hard, unyielding masses. Thus, loose sand has been solidified into sandstone, while sandstone, in its turn, has been highly indurated and changed into quartz-rock. Another result of the circulation of such solutions has been the filling-up of cracks, fissures, and cavities of all shapes and sizes, in almost every kind of rock. Hence, quartz frequently appears in the form of ramifying veins and veinlets, and is one of the commonest minerals associated with ores in lodes. 4. As quartz resists decomposition and is the commonest of all rock-forming minerals, it enters conspicuously into the formation of a large number of sedimentary rocks. These, as we shall learn, are simply residual products—that is to say, they have been derived from the disintegration and degradation of pre-existing rock-masses; and quartz, in consequence of its superior durability, its great abundance, and wide distribution, naturally forms a dominant ingredient of conglomerates, greywackés, sandstones, etc.

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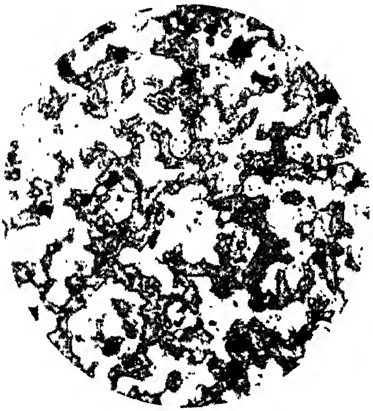
* See Appendix B.

In coarsely crystalline rocks, quartz, even when it shows no external crystalline form, is quite readily recognised by its other physical characters—namely, by its hardness, its conchoidal fracture and absence of cleavage, its vitreous lustre, and the lack of any trace of decomposition. In coarse-grained granite, for example, it appears like a kind of transparent cement, filling up the straggling spaces between the other mineral ingredients, which it thus seems to bind together. In certain other eruptive rocks, as in quartz-porphyry, pitchstone, etc., it often occurs as conspicuous, corroded, but occasionally well-formed crystals, disseminated through a groundmass of fine-grained materials (see Plate II. 3). The best-developed quartz crystals met with in eruptive rocks, however, are found in certain curious irregular cavities which frequently appear in granite. The walls of such cavities are usually lined with fine crystals of the several mineral constituents of the rock, amongst which hexagonal prisms and "pyramids" of quartz are commonly prominent (see Plate IX. 2).

In finely crystalline rocks, the presence of quartz can only be determined by microscopic examination. In thin slices it appears limpid, water-clear,

PLATE II

Microscopic Structure of Minerals and Rocks



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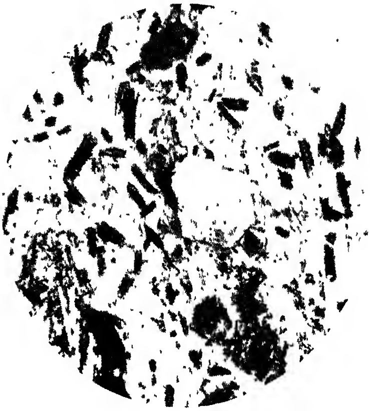

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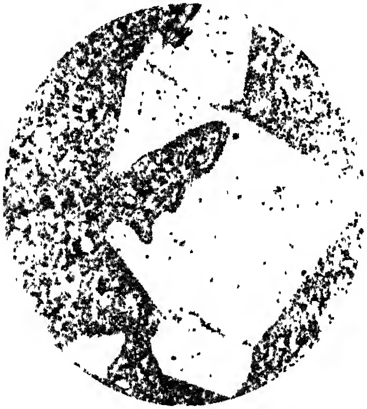

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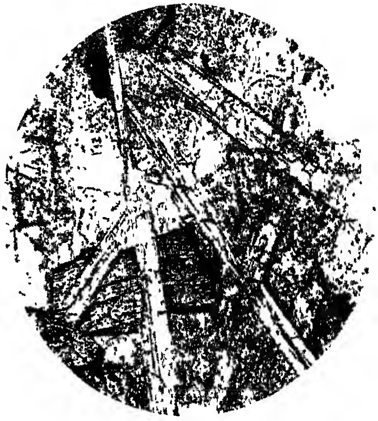

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1. Leucite—small circular sections with inclusions. Leucitite, Capo di Bove. × 35.
2. Nepheline, transverse section of, near centre. Phonolite, Wolf Rock, Cornwall. × 80.
3. Corroded Quartz phenocryst in Quartz-porphyry, Penhale Moor, Cornwall. × 20.
4. Acicular crystals of Apatite. Theralite, Barshaw Park, Paisley. × 55.

[*To face page* 5

and quite unaltered. It shows no trace of cleavage, but is traversed by numerous irregular cracks. The surface appears smooth, and neither bounding edges nor internal cracks are pronounced. When crystals of the mineral are present (as in quartz-porphyry), they usually show lozenge-shaped outlines with rounded angles. According to the thickness of the slice, and the direction of the section, the polarisation colours vary in intensity, but, since the mineral has weak double refraction, they are always low.

Enclosures of other minerals are common in quartz. In large crystals these are often visible to the naked eye (see Plate I. 2). Under the microscope even the smallest granules of the quartz of eruptive rocks, such as granite, may appear crowded with inclusions of rutile, apatite, and other minerals. The quartz of granite also usually contains numerous minute fluid cavities, more or less irregularly disseminated through the mineral, while the quartz of pitchstones, rhyolites, and quartz-porphyries frequently encloses minute quantities of glass or stone.

The chief varieties of quartz are the following:—*Rock-crystal*, water-clear; *Avanturine*, rock-crystal, abundantly spangled with enclosed scales of mica or other mineral; *Amethystine Quartz*, violet-coloured rock-crystal; *Smoky Quartz* including dusty-brown to black (*Morion*) and paler brown to yellow (*Cairngorm*) rock-crystal; *Milky Quartz*, milk-white and nearly opaque, with a somewhat greasy lustre; *Common Quartz*, not transparent, white, but occasionally coloured, sometimes with crystalline form, but usually massive.

Chalcedony (SiO_2) is a secondary mineral, which may occur in almost any kind of siliceous rock. It frequently lines or fills vesicles, fissures, and other cavities in igneous rocks, and is common in metalliferous veins or lodes. It is translucent and has a somewhat waxy lustre. The colour varies, the commoner kinds being white or grey, but brown or black, and yellowish-green and blue varieties are known. It frequently shows a banded structure, and often assumes nodular, mammillary, botryoidal, reniform, or stalactitic shapes, being obviously in such cases a deposition from aqueous solution. When a thin slice of a spherical concretion is seen under the microscope, chalcedony exhibits a finely fibrous radiating texture, and between crossed nicol prisms shows a black cross, which remains stationary while the slide is being rotated. The optical characters of the fibres prove that chalcedony is a separate mineral species, not a variety of quartz. Under chalcedony are included the following:—*Carnelian*, translucent red; *Chrysoprase*, apple-green; *Plasma*, dark leek-green, but when spotted with carnelian known as *Heliotrope* or *Bloodstone*; *Agate*, essentially a variegated chalcedony the colours being either banded or in clouds, or due to visible impurities, but sometimes in part quartz or opal. In *Banded Agate* the layers are wavy or zigzag, or concentric and more or less spherical, according to the conditions of deposition, and the shape of the cavity occupied by the mineral (Plate I. 1). In *Clouded Agate* the variously coloured portions are irregularly distributed. When visible impurities in a chalcedony assume moss-like or dendritic shapes, we have the variety known as *Moss Agate*. *Onyx* is an agate in which the coloured layers occur in even planes; when one of these is dark brown, overlaid by a bluish-white layer, the mineral is used for cameos—the figure being carved in the white layer, while the dark layer serves for a background. *Sardonyx* is an onyx consisting of alternate layers of carnelian and opalescent chalcedony. The term *Jasper* has been applied both to opaque red or brown varieties of chalcedony, and to finely crystalline aggregates of quartz intimately mixed with red or yellow hydrates of iron. *Flint* is allied to chalcedony, consisting of cryptocrystalline silica, but rendered opaque owing to abundant impurities; it has a marked conchoidal fracture. *Chert* (including *Hornstone*) differs little from flint: the fracture is splintery rather than conchoidal. Flint and chert occur chiefly in calcareous rocks, in the form of nodules, layers, or irregular concretions.

Opal is an amorphous mineral (*i.e.*, devoid both of external crystalline form and internal crystalline structure). It is composed of silica, with a variable proportion of water (usually from about 3 to 10 per cent.); the specific gravity of the mineral (1·9 to 2·3) is somewhat less than that of quartz, and the same is the case with the hardness (5·5 to 6·5). The texture is colloidal or jelly-like, and the lustre vitreous to resinous. The colour varies—it may be white, red, brown, yellow, green, or blue, and some kinds show a rich play of colours. Opal usually occurs in reniform, botryoidal, or stalactitic masses, occupying any irregular cavity in rocks. In all cases it is of secondary origin—that is, it has been subsequently introduced as a product of decomposition. Many varieties are recognised, among which the following may be mentioned: *Siliceous Sinter* or *Geyserite*, deposited from thermal waters, often loose and earthy; *Hyalite*, usually water-clear, colourless, but sometimes white or translucent—it occurs in the joints, fissures, and vesicular cavities of some basalts; *Noble* or *Precious Opal*, with a rich play of colours, met with in irregular cavities in trachyte, etc.; *Common Opal*, translucent, but showing no play of colours, in veins, fissures, etc., in igneous rocks; *Semi-Opal*, less translucent than common opal; *Jasp-Opal*, red or brown in colour; *Menilite*, an opaque greyish or brown concretionary opal, occurring occasionally in argillaceous rocks.

Weathering of Quartz, Chalcedony, and Opal.—While the crystallised varieties of silica remain practically unaffected by the chemical action of percolating water, the cryptocrystalline and amorphous forms are not so resistant, but frequently "weather" with a white crust.

Hæmatite, oxide of iron (Fe_2O_3), crystallises in trigonal forms, commonly combinations of rhombohedra and scalenohedra. It has a hardness of 5·5 to 6·5, and a specific gravity of 5·19 to 5·28; crystals are bluish iron-grey in colour, while fibrous forms are usually brownish-red. The mineral yields a red powder when rubbed with a steel file. This red streak and the absence of magnetism distinguish hæmatite from magnetite. It occurs both crystalline and massive. The crystalline variety is common in veins, and is often accompanied by magnetite. Not infrequently it occurs as an ingredient of igneous and metamorphic rocks. It is met with in many minerals as a microscopic inclusion (*endomorph*), in the form of minute filmy plates or scales, the presence of which affects the colour of the including mineral (*perimorph*), and often imparts to it a kind of pearly or sub-metallic glimmer or iridescence. Now and again it has been developed in limestones at or near their point of contact with eruptive rocks. It occurs as a sublimation-product in volcanic regions. Crystalline hæmatite, because of its splendent, metallic lustre, is often called *specular iron*, or, if the crystals are thin and tabular, it is known as *micaceous hæmatite.*

The more compact or cryptocrystalline varieties of hæmatite usually occur as veins, irregular beds, and masses. *Kidney-ore* is the name given to nodules and nodular masses, which often consist of concentric coats having a radiating structure. Hæmatite frequently occurs in decomposing igneous rocks as an alteration-product of ferromagnesian minerals, and it often coats the faces of joints in these and other ferriferous rocks. It is probable, however, that the ferruginous mineral commonly seen on joint-faces is in many cases not true hæmatite, but *Hydro-hæmatite* or *Turgite*, which contains a small percentage of water—only 5 per cent. In other respects it is so closely similar to hæmatite that it can only be differentiated from the latter by analysis.

Limonite ($Fe_2O_3 . nH_2O$) occurs as fibrous aggregates, assuming nodular, stalactitic, or botryoidal forms, or as large irregular masses. Its hardness is 4 or thereabout, but earthy varieties are softer; the specific gravity = 3·4 to 3·95. It is brown or yellowish-brown, and has a yellow-brown streak. As a rock-constituent it is always a product of alteration—derived from the decomposition of minerals which contain iron. Limonite is itself amorphous, but often has the outward crystalline shapes of other minerals, that is, it is occurring as *pseudomorphs* after these minerals.

Spinel Group (Spinel, Magnetite, Chromite). The minerals of the Spinel Group may be regarded as double oxides of the trivalent and divalent elements. The commonest varieties are *Magnetite* ($FeO . Fe_2O_3$), *Chromite* ($FeO . Cr_2O_3$), *Spinel* ($MgO . Al_2O_3$), *Ceylonite* or *Pleonaste* $\{(Mg, Fe)O . Al_2O_3\}$ and *Picotite* $\{(Mg, Fe)O . (Al, Fe, Cr)_2O_3\}$. All are isometric, and, although sometimes found in granules and granular aggregates, occur very characteristically as simple octahedral crystals.

Magnetite is iron black in colour and its streak is black. It is strongly magnetic. It has a hardness of 6 and its specific gravity is 5·17. It is very readily soluble in hydrochloric acid. On decomposition magnetite changes to hæmatite, limonite, or siderite. It should be noted, however, that varieties in which the ferric iron is largely replaced by titanium (*titanomagnetite*) are quite common, and in these, as in *ilmenite*, leucoxene, a variety of titanite, is a frequent alteration-product. In thin slices magnetite is opaque and shows a steel blue colour when viewed with oblique reflected light.

Magnetite is a widely distributed rock-former. As an accessory constituent it is found in all kinds of igneous rocks, somewhat sparingly in acid types, and abundantly in many basic types. Sometimes indeed it forms large bodies of igneous origin which are of commercial importance. It is equally widely distributed in crystalline metamorphic rocks, and many large deposits of magnetite are regarded as resulting from the metamorphism of original deposits of hæmatite or limonite. It is found also in detrital deposits and, together with ilmenite, is very abundant in the "black sands" derived from the disintegration of basic eruptive rocks, etc.

Chromite occurs most frequently as granular anhedral crystals, iron-black to brownish-black in colour. It has hardness 5·5 and specific gravity 4·5, and shows much less magnetism than magnetite. In thin section it is isotropic and distinguished by its deep brown to yellowish-red colour and very high refractive index.

As a rock-constituent chromite is found, often highly segregated, in basic and ultrabasic igneous rocks such as norites, peridotites, and serpentines; it occurs also in metamorphic rocks such as talc schists and talc-carbonate schists. Workable bodies of chromite are of great economic importance, since this is the chief mineral from which salts of chromium are obtained for industrial purposes.

Spinel appears as simple octahedral crystals showing imperfect octahedral cleavage. It is characterised by very great hardness (8); its specific gravity is 3·6. The colour of the mineral is variable—shades of red, yellow, pale green, and blue. The more transparent kinds are of value as gemstones, the red crystals being known as "spinel-ruby" or "balas-ruby," the golden-yellow or orange-red as "rubicelle" and the violet as "almandine-spinel." Precious spinel occurs for the most part in crystalline limestones and dolomites, but is met with also in some schists.

Ceylonite or **Pleonaste,** green, brown, or black in colour, is found occasionally as an accessory mineral in igneous rocks (Plate XVI. 2), but occurs chiefly in rocks belonging to zones of contact metamorphism. **Picotite,** in small yellow and brown crystals, often enclosed in olivine, has a distribution as a rock-former similar to that of chromite.

In thin sections the spinels may be confused with certain varieties of garnet because of their similarity in colour (lighter shades of the hand specimen colours), their isotropic character and high refractive indices. The spinels, however, may be distinguished in most cases by their octahedral form and by the presence of cleavage.

Ilmenite ($FeTiO_3$) may have as much as 30 per cent. of hæmatite in solid solution, and the formula of common rock-forming ilmenite may be stated as $FeTiO_3.nFe_2O_3$. It crystallises in the trigonal system. The crystals have hardness 5·5 and specific gravity 4·6 to 4·9. In hand specimens the mineral is iron-black in colour; the streak is black to brownish-red. It is feebly magnetic and is only slowly soluble in hydrochloric acid. In thin section ilmenite is opaque with transmitted light and iron-black in reflected light, except when it contains much Fe_2O_3, in which case it becomes brownish-black. The characteristic product of its decomposition is leucoxene (see under *titanite*). Ilmenite can be distinguished from ordinary magnetite by its feebler magnetism and by its slow solubility in hydrochloric acid, which also serves to distinguish it from hæmatite. From titanomagnetite it can be distinguished only when the crystals are euhedral.

Ilmenite is widely distributed as an accessory constituent of basic igneous rocks and is the chief component of certain ultrabasic rocks such as the ilmenitites of southern Norway. It is found also in detrital and metamorphic rocks.

Rutile (TiO_2) as a rock-former occurs usually as minute dark brown or reddish grains, pointed prisms and knee-shaped (Fig. 2) or heart-shaped twin-crystals belonging to the tetragonal system. Hair-like needles may be seen sometimes enclosed in rock crystal (see Plate I. 2). Larger crystals in the form of elongated square prisms with brilliant adamantine lustre are found in vein quartz. The mineral is hard and heavy, its hardness being

6 to 6·5 and its specific gravity 4·18 to 4·25. In thin slices it may be recognised by its reddish-brown to yellow colour, its characteristic twinning, its high relief, and its extremely strong birefringence.

Rutile is widely distributed as a rock-former in crystalline metamorphic rocks. As it is not readily attacked by the ordinary agents of decomposition it is of common occurrence also in clastic derivative rocks. Small needle-like crystals are often abundant in clay-slates. In igneous rocks it is seldom met with as a primary constituent, but it is of not infrequent occurrence as a secondary mineral formed from the alteration of various titanium-bearing minerals.

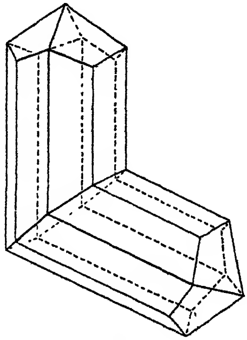


FIG. 2.—CRYSTAL OF RUTILE.
A knee-shaped (geniculate) twin.

Corundum (Al_2O_3) crystallises in hexagonal prisms and steep hexagonal pyramids, which are often rough and rounded. It is a very hard mineral (9 in the scale), and has a high specific gravity (3·9 to 4). It is insoluble in acids. *Common corundum* includes varieties with dark or dull colours; the clear, transparent to translucent, brightly coloured varieties are valuable as gemstones and include *sapphire*, blue, *ruby*, red, *oriental topaz*, yellow, *oriental emerald*, green, etc.; *emery* is an intimate mixture of dark corundum, magnetite, and hæmatite. In thin slices corundum shows very high relief and weak birefringence, and pleochroism is distinct in the deeply coloured varieties.

Corundum is fairly widely distributed as a constituent of crystalline metamorphic rocks such as marble, mica schist, and gneiss; it is often an important component of fine-grained hornfelses in zones of contact metamorphism. Although it is not a common constituent of igneous rocks, it occasionally is abundant, as in the corundum-rich aplites of South Africa and the corundum-syenites and corundum-anorthosites of Canada. Because of its resistance to weathering it is also found in many stream gravels and sands.

Pyrolusite, Psilomelane, and **Wad** (oxides of manganese) are also unimportant rock-formers, but they often appear (particularly psilomelane) as thin films coating the walls of cracks and fissures or the surfaces of bedding-planes in various kinds of rock. The films often assume plant-like forms ("dendritic markings," see Plate XXX.). The earthy varieties of these oxides occasionally form bedded masses.

II. SILICATES

FELDSPAR GROUP

Feldspar is a general term for a number of closely related minerals which play a very important rôle as rock-formers. They are the chief constituents of most eruptive rocks, and are met with likewise more or less abundantly in many crystalline schists. They vary in colour, but are usually grey, white, or reddish; occasionally, however, they show yellow, green, or blue tints. As rock-constituents they frequently assume the form of tabular crystals, or appear as rectangular lath-shaped bodies. All are characterised by two well-marked sets of cleavage-planes (at, or nearly at, right angles) which show usually a glassy or pearly lustre; further, all have approximately the same hardness (6 to 6·5), and specific gravity (2·54 to 2·76). Chemically, they are silicates of aluminium with potassium, sodium, or calcium (rarely barium). Hence we have potash feldspar, soda feldspar, lime feldspar, soda-lime feldspar, etc. These feldspars so closely resemble each other that it is often hard or even impossible to distinguish one from another by the unassisted eye. This, of course, is especially the case when the crystals are small. Usually, however, the particular class or series to which a feldspar belongs can be determined by examination in thin slices under the microscope. Two series of feldspars are recognised—one of these crystallising in monoclinic and the other in triclinic forms. The monoclinic series includes Orthoclase and Sanidine, while the triclinic class is represented by Microcline, Anorthoclase, and Plagioclase—the last-named forming a group of feldspars which are all closely related, and often hardly to be distinguished from each other without careful microscopical or chemical examination. Orthoclase and Plagioclase can be distinguished—as the names suggest—by the difference in the cleavage angles. Both have good pinacoidal cleavage in two directions, that parallel to the basal plane being in each case the more perfect, but in Orthoclase the cleavages are rectangular, while in the Plagioclases the cleavage angles vary from 93° 34′ to 94° 12′.

If feldspars always assumed their external crystalline form and were of sufficient size, it would not be hard to distinguish between orthoclase and plagioclase. As rock-constituents, however, they are often so unsymmetric in shape, or occur as granules so small in size, that the geologist must have recourse to other differentiating characters to distinguish between one feldspar and another. Under the microscope, the plagioclase feldspars can usually be recognised by their "multiple twinning." A crystal or crystalline granule having this structure appears as if it were composed of a series of parallel plates or lamellæ, which show alternately lighter and darker tints when examined between crossed nicols. Thus a section of the mineral, if cut in a proper direction, exhibits a banded or striped appearance (Plate

III. 2). Not infrequently the twinned structure can be seen by the naked eye or with the aid of a pocket-lens, when the feldspars are fresh and not too small. The structure is revealed by the appearance of fine parallel lines, best seen on basal cleavage planes—the lines marking, of course, the junction of separate twin lamellæ. The twinning of orthoclase feldspars is "simple" (Fig. 3), so that a section cut in the right direction shows between crossed nicols only two differently tinted bands (see Plate III. 1). When the mineral is not twinned, or when the section is cut parallel to the twinning plane, feldspars polarise in one uniform colour. The feldspars all have low relief and weak double refraction. The most rapid and satisfactory mode of identifying the many varieties is by indirect determination of the refractive indices, which vary with the chemical composition, by the oil immersion method. Determination by measurement of extinction angles in sections of known orientation presents greater difficulties for the beginner.

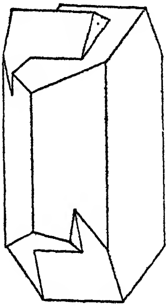


FIG. 3. — CRYSTAL OF ORTHOCLASE: CARLSBAD TWIN.

Orthoclase ($KAlSi_3O_8$) is usually white, grey, or reddish. It is not attacked by ordinary acids but is decomposed by hydrofluoric acid. As a rock-former it occurs most frequently as imperfect crystals, or irregular crystalline aggregates. In certain igneous rocks, however (as in quartz-porphyry), it appears as conspicuous and sometimes well-formed crystals disseminated among the finer-grained constituents of the mass. Fine crystals of orthoclase often occur in drusy cavities and veins in granite, and now and again in fissures traversing crystalline schistose rocks. The mineral is an essential ingredient of many eruptive rocks (granite, quartz-porphyry, syenite, etc.). It is readily distinguished from quartz by its hardness, cleavage, twinning, and frequent turbidity—due to gradual alteration of the mineral into kaolin and other decomposition products. Its mean refractive index is 1·524.

Sanidine is a glassy clear variety of orthoclase, usually much cracked, and often crowded with inclusions. It is the type of orthoclase which characterises volcanic rocks—rhyolite, trachyte, phonolite, etc., and frequently assumes the form of tabular crystals (see Plate III. 1).

Microcline (triclinic potash feldspar) has the same chemical composition as orthoclase, from which it can hardly be distinguished without examination under the microscope. It is a frequent constituent of granite, appearing often in well-developed forms in the drusy cavities and the pegmatite veins associated with that rock. It occurs also in certain syenites and other eruptive rocks of deep-seated origin, and is occasionally present in gneiss. Although it thus frequently accompanies orthoclase proper, it has not yet been met with in rocks that contain the glassy variety of that mineral—sanidine. Under the microscope, microcline usually shows a polysynthetic structure, due to the presence of minute spindle-shaped twin lamellæ, so arranged that, when the section is cut in a particular direction, it has in polarised light a peculiar cross-hatched appearance (see Plate III. 3). Its mean refractive index is 1·526.

Anorthoclase or **Soda Microcline** $(Na, K)AlSi_3O_8$ shows much the same structure under the microscope as microcline, but usually on an exceedingly minute scale. It has a slightly higher mean refractive index, 1·529. It occurs only in igneous rocks rich in soda such as the well-known rhomb-porphyries of Southern Norway.

The potash feldspars generally weather readily into kaolin. Not infrequently, however, they are transformed into other minerals—muscovite (potash mica) and quartz often replacing orthoclase.

The **Plagioclase** feldspars sometimes occur in crystalline masses. As rock-formers, however, they usually appear as elongate tabular crystals, not infrequently grouped in bundles or forming radiating aggregates, or they may be mere crystalline granules. They form a series, of which *Albite* $(NaAlSi_3O_8)$ and *Anorthite* $(CaAl_2Si_2O_8)$ are the two extremes. The intermediate forms are regarded as isomorphous mixtures of these two silicates in various proportions, as shown in the following table, where Ab stands for albite and An for anorthite :—

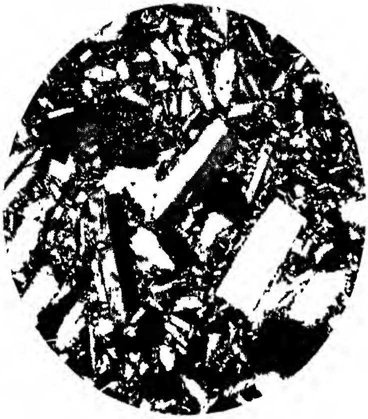
Albite $(Ab_{100}\ An_0)$.
Oligoclase $(Ab_{80}\ An_{20})$.
Andesine $(Ab_{60}\ An_{40})$.
Labradorite $(Ab_{40}\ An_{60})$.
Bytownite $(Ab_{20}\ An_{80})$.
Anorthite $(Ab_0\ An_{100})$.

The silica percentage ranges from 43·2 in anorthite to 68·8 in albite. Anorthite is decomposed by hydrochloric acid with gelatinisation, while albite resists ordinary acids—the intermediate varieties becoming more readily affected the nearer they approach in composition to anorthite. All are subject more or less readily to alteration, being transformed especially into such minerals as kaolin, sericite (a variety of muscovite), epidote, calcite, zeolites, etc. *Saussurite* is the name given to an altered plagioclase which often occurs in gabbro. It is fine-grained to compact, grey, ash-grey, or greenish-white, shimmering or dull, and translucent on thin edges.

Well-developed and more or less perfect crystals of plagioclase often occur in the drusy cavities of eruptive rocks, in

PLATE III

Microscopic Structure of Minerals and Rocks



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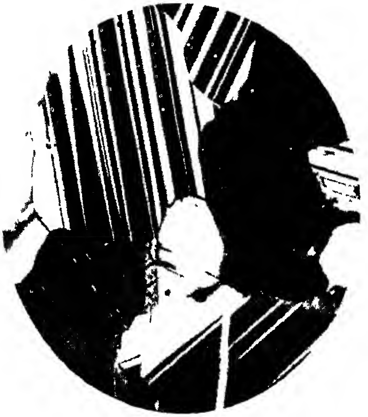

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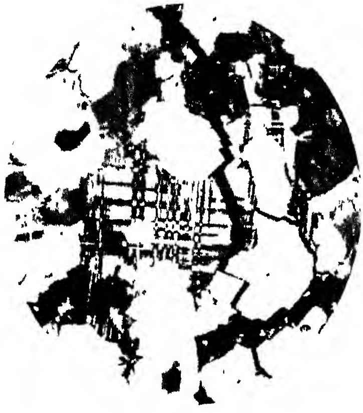

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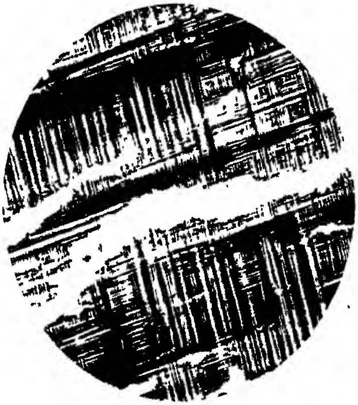

4.

1. Sanidine showing simple twinning on Carlsbad law. Trachyte, Hohenberg, Rheinpr. Nicols crossed. ×35.
2. Plagioclase showing multiple twinning on Albite law. Anorthosite, Roineval, S. Harris. Nicols crossed. ×25.
3. Microcline, near centre, showing cross-hatching. Granite-gneiss, S. Harris. Nicols crossed. ×20.
4. Microcline-perthite. Intercalations of albite (white) in microcline. Nicols crossed. ×35.

fissures in crystalline schists, and in blocks ejected from volcanoes. The plagioclase feldspars are among the most important rock-formers, occurring as primary constituents of a large number of eruptive rocks both as macroscopic and microscopic individuals. They have also a wide distribution amongst the crystalline schists. The feldspars (monoclinic and triclinic alike), being readily weathered and decomposed, are met with in noteworthy amount in derivative rocks only in types such as arkoses and greywackés, which have been formed under exceptional conditions of disintegration and deposition.

A few notes on the individual plagioclase feldspars may be added:—

Albite: usually white; resembles orthoclase, from which it may be distinguished by its greater specific gravity (orthoclase, 2·54 to 2·58; albite, 2·61 to 2·64), its higher refractive index, 1·529 and the character of its twinning. Regular intergrowths of orthoclase (or microcline) and albite are known as *perthite* (see Plate III. 4), or, if the albite intercalations are on a microscopic scale, as *microperthite*. Apart from its occurrence in perthitic feldspars, which are common in syenitic rocks, albite cannot be described as an important constituent of igneous rocks. It is a common ingredient, however, of certain crystalline schists. Now and again it occurs as a "contact mineral" in argillaceous rocks, near their junction or contact with intrusive eruptive rocks.

Oligoclase is a common constituent of many eruptive rocks, especially of those in which quartz or orthoclase, or both together, occur as important ingredients, as in syenite and granite. It is present likewise in some diorites, microdiorites, and andesites. It is common also in gneisses and schists. Its mean refractive index is 1·546.

Andesine is a frequent constituent of certain eruptive rocks, such as diorite and andesite and occurs often also in gneisses and schists. Its mean refractive index is 1·556.

Labradorite is a common constituent of gabbros, norites, basalts, and dolerites. It is the chief constituent of anorthosites, where it frequently shows a very fine play of colours, due to the interposition, along certain planes, of minute platy inclusions. Its mean refractive index is 1·560.

Bytownite occurs not uncommonly in basalts and other basic eruptive rocks. Its mean refractive index is 1·570.

Anorthite occurs not infrequently as a constituent of basic igneous rocks, as in some gabbros and peridotites. It is also an occasional constituent of metamorphic rocks. Its mean refractive index is 1·580.

The Feldspathoid Group

The feldspathoids (*Leucite*, *Nepheline*, *Sodalite*, *Haüyne*, *Nosean*, and *Analcite*), although less highly silicated compounds, are akin to the feldspars in consisting mainly of aluminous silicates of potash, soda, and lime. They crystallise, however, in systems of higher symmetry, the cubic and the hexagonal. They are much less widely distributed as rock-formers, being restricted to certain alkali-rich igneous rocks. They never occur as ingredients of the crystalline schists.

Leucite ($KAlSi_2O_6$) generally appears in the form of more or less well-defined single crystals, having the shape of icositetrahedra (24-faced trapezohedra). In cross-sections the larger crystals often yield six-sided or eight-sided contours, while the smaller crystals are rounded. The mineral has a hardness of 5·5 to 6, and a specific gravity of 2·47. If pure, it is transparent and colourless, but most frequently, owing to the presence of impurities, it appears ash-grey or greyish-yellow, and then it is only translucent on thin edges. When reduced to a powder it readily dissolves in hydrochloric acid, with separation of pulverulent silica. Under the microscope, leucite usually shows abundant symmetrically-arranged inclusions of glass, gas pores, and minute microlites, grains, etc., of such minerals as feldspar, augite, and magnetite (see Plate II. 1). Between crossed nicol-prisms it exhibits weak, anomalous double refraction—yielding dark grey colours—the crystals being traversed by intersecting alternately light and dark twin lamellæ. This structure, however, is not seen in the smaller crystals, which are usually isotropic. The mineral is readily altered in nature, becoming white and opaque as it is changed into analcite, zeolites, or kaolin. Probably its proneness to alteration is the reason why it seldom occurs in very old igneous rocks. It is a macroscopic and microscopic constituent of many Vesuvian lavas. In the so-called *pseudoleucites* of certain Palæozoic rocks original leucite has been pseudomorphed, sometimes by orthoclase and nepheline, sometimes by orthoclase (or albite) and sericite, or sometimes by analcite.

Nepheline is essentially $NaAlSiO_4$, but contains varying amounts of $KAlSiO_4$. It has a hardness of 5·5 to 6 and its specific gravity ranges from 2·55 to 2·65. As a rock-constituent it appears in the form of hexagonal prisms (see Plate II. 2) with a glassy lustre, and is either water-clear or white. A variety with a greasy lustre, brownish to grey in colour, and often abundant in certain syenites, has been named *elæolite*. The mineral has low relief (the mean refractive index is approximately that of the Canada balsam with which rock slices are mounted), and its double refraction is very weak. Nepheline gelatinises readily with acids, and, like leucite, is very unstable. Its alteration-products are variable—sometimes the mineral is replaced by aggregates of muscovite and calcite, sometimes by fibrous zeolites or analcite or cancrinite. Nepheline occurs only in igneous rocks relatively rich in soda such as nepheline syenite, phonolite, nepheline basanite, nepheline basalt, etc.

Sodalite ($3NaAlSiO_4 . NaCl$) crystallises in dodecahedra and has imperfect dodecahedral cleavage. It has a hardness of 5·5 to 6 and its specific gravity is 2·14 to 2·4. It gelatinises even in the weakest acids, and when powdered yields NaCl if treated with boiling water. Common alteration-products of this mineral are fibrous zeolites, aggregates of colourless micas, cancrinite and calcite. It has a very low refractive index (1·483) and is isotropic. The colour of sodalite in hand specimens is variable, but in thin slices it is usually colourless. A blue variety is conspicuous in some syenites. The mineral is found only in soda-rich igneous rocks.

Nosean ($6NaAlSiO_4 . Na_2SO_4$) and **Haüyne** ($3NaAlSiO_4 . CaSO_4$) are similar to sodalite in their crystallographic and other physical properties and in their modes of decomposition. They can be distinguished from one another and from sodalite most easily by microchemical tests. They are of common occurrence as accessory minerals in nepheline-rich and leucite-rich rocks such as phonolites, tephrites, and basanites.

Analcite ($NaAlSi_2O_6 . H_2O$) is a colourless to white mineral, with vitreous lustre, which crystallises in the cubic system, not infrequently as simple icositetrahedra. It has imperfect cubic cleavage. It has a hardness of 5 to 5·5 and its specific gravity is 2·22 to 2·29. The refractive index of analcite is very low (1·487); it is mostly isotropic but sometimes shows anomalous weak double refraction. It gelatinises with hydrochloric acid. Analcite is an important primary constituent of many basic alkaline igneous rocks and it has a wide distribution also as a secondary mineral, usually associated with zeolites.

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CHAPTER II

ROCK-FORMING MINERALS—*continued*

Silicates—Mica Group; Amphibole Group; Pyroxene Group; Olivine Group; Chlorite Group; Talc Group; Glauconite Group; Epidote Group; Garnet Group; Zircon Group; Titanite; Tourmaline Group; Andalusite Group; Cordierite; Zeolite Group; Kaolinite Group. Haloids — Fluorite and Rock-Salt. Sulphides — Pyrite, Pyrrhotite, and Marcasite. Carbonates — Calcite, Aragonite, Dolomite, and Siderite. Sulphates—Anhydrite, Gypsum, and Barytes. Phosphates —Apatite, etc. Elements—Graphite.

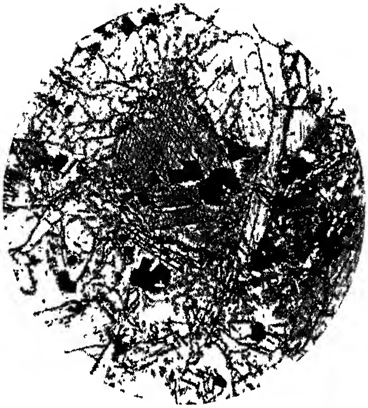
THE MICA GROUP

THE **Micas,** as rock-formers, mostly occur as six-sided tabular crystals or as minute scales. They are all monoclinic, but, when euhedral, show pseudo-hexagonal symmetry. They have perfect cleavage in one direction, parallel to the basal pinacoid, and can be cleaved very easily into thin, transparent, elastic laminæ. They are all rather soft (2·5 to 4 in the scale) and their specific gravity ranges from 2·75 to 3·4. They are highly lustrous, vitreous, or pearly or sub-metallic. Only two micas are important as rock-formers, namely, the brown to black **Biotite** or ferromagnesian mica, and the silver-white **Muscovite** or potash mica. They are essential minerals in many igneous and metamorphic rocks and are frequent products of the alteration of other silicates in such rocks; muscovite—sometimes accompanied in small amount by frayed scales of biotite—is a characteristic mineral of mechanically-formed derivative rocks, and is particularly conspicuous in some flaggy sandstones.

Biotite $\{H_4K_2(Mg, Fe)_6Al_2Si_6O_{24}\}$, when fresh, is usually black or very dark in colour. When weathered it changes, through loss of alkalies, to a brownish or golden-yellow alteration-product consisting of soft, flexible, inelastic laminæ; or, particularly when it has been subjected to hydrothermal action, it may be partly or completely replaced by green

PLATE IV

Microscopic Structure of Minerals and Rocks



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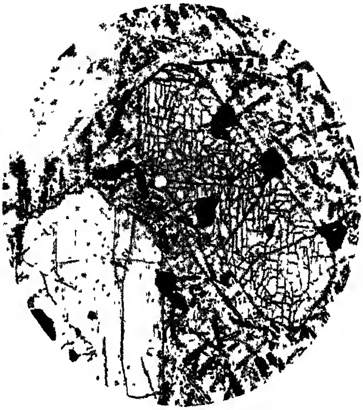

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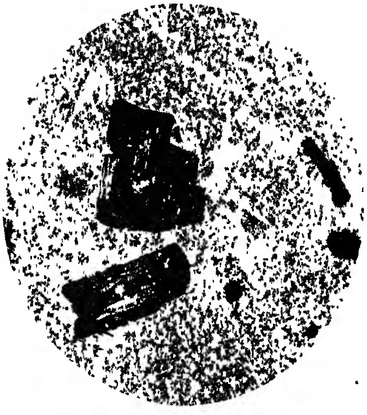

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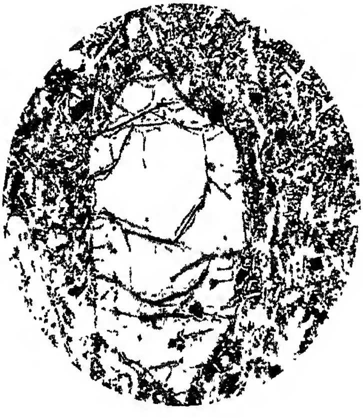


4.

1. Euhedral crystal of Hornblende in transverse section, with characteristic outline and cleavages; it encloses apatite and magnetite. Teschenite, Neutitschein. ×35.
2. Euhedral crystal of Titanaugite in transverse section, with characteristic outline and cleavages; it encloses magnetite and apatite. Monchiquite, Peak of Tingua, Rio de Janeiro. ×35.
3. Phenocrysts of Biotite showing perfect basal cleavage. They enclose apatite. Quartz-porphyry, Clochnahill, Kincardineshire. ×20.
4. Euhedral crystal of Olivine in longitudinal section, showing characteristic shape and fracture: incipient serpentinisation along cracks. Basalt, Orrock Quarry, Fife. ×35.

[*To face page* 16

chlorite and iron oxides. In thin slices under the microscope, cleavage-plates are six-sided and deep brown, deep green or sometimes almost black and show little or no change of colour when rotated above the polariser; sections cut across the cleavage planes, which then appear as a series of parallel lines traversing the mica (see Plate IV. 3), are strongly dichroic. The refractive index is moderately high, and the strong double refraction is apparent from the brilliant polarisation colours given by longitudinal sections. Inclusions of other minerals, chiefly magnetite, apatite, zircon, and rutile, are very common, and a noteworthy feature of many biotites is the fine development of pleochroic halos round the small included zircons.

Biotite is an important primary constituent of igneous rocks. It is particularly abundant in acid types such as granites and rhyolites, but occurs frequently also in many syenites, diorites, trachytes, and andesites and occasionally in the more basic rocks. It is common also in crystalline metamorphic rocks. It is found less frequently than muscovite in sedimentary rocks because of its susceptibility to attack by weathering agents. *Phlogopite*, a magnesian mica with little or no iron, is developed in metamorphosed impure dolomites.

Muscovite $\{H_4K_2(Al, Fe)_6Si_6O_{24}\}$ is sometimes colourless but is usually pale-coloured or silvery; occasionally it assumes a light shade of brown or green. It is insoluble in acids and offers strong resistance to the ordinary agents of weathering. Seen under the microscope it is colourless, unweathered, has perfect cleavage in one direction, has very distinct relief and shows very strong birefringence. Inclusions are few in number.

As a primary constituent of igneous rocks, muscovite is confined to acid types such as granite, greisen, pegmatite, and aplite. It is widely distributed in gneiss, mica schist, and related rocks. As a secondary mineral it occurs in minute scales, often called *sericite*, in all kinds of rock as a product of the alteration of other aluminous alkali-rich silicates. It is also a common constituent in sedimentary rocks.

The Amphibole Group

The **Amphiboles** described here are calcium-magnesium silicates, some being rich in aluminium and iron, others containing little or no trace of either. Of less frequent occurrence are varieties rich in soda. When crystallised they appear as prisms; but they show a marked tendency to assume fibrous and radiated forms. They crystallise in monoclinic or, less often, orthorhombic forms, but only the former are abundant as rock-formers. A distinctive feature of all the amphiboles is perfect prismatic cleavage in two directions at an angle of about 124° (see Plate IV. 1). Their specific gravity ranges from 2·9 to 3·5, and their hardness is between 4 and 6.

The *monoclinic non-aluminous amphiboles* are lighter in colour than those rich in aluminium and iron. The most commonly occurring representatives of the non-aluminous class are Tremolite and Actinolite.

Tremolite ($H_2Ca_2Mg_5Si_8O_{24}$) is white, grey, or light green in colour, and occurs usually in the form of long blade-shaped crystals, striated longitudinally: or it assumes the appearance of thin fibrous crystals radiating from a centre. The crystals have a pearly or silky lustre. This mineral is a constituent of some schistose rocks; it occurs not uncommonly in crystalline limestone and dolomite (marble) near their point of contact with plutonic rocks. Now and again it is met with as an alteration-product in olivine-rocks and serpentine. **Actinolite** differs from tremolite in containing a considerable percentage of iron; hence it is generally light or dark green in colour. It usually occurs as long thin columnar crystals and radiate aggregates. It is a common ingredient of many crystalline schists, where it is frequently associated with talc, chlorite, and epidote. In eruptive rocks (as in saussurite-gabbro) it is often met with as an alteration-product.

Tremolite and actinolite sometimes assume forms so fibrous that they can be readily separated into thin, soft, cotton-like, or silky threads, and are then known as **Amianthus** or **Asbestos**. The fibres are often matted together so as to form felt-like substances, termed "mountain-leather," "mountain-cork," etc. Most of the asbestos of commerce, however, is not amphibole, but fibrous serpentine (chrysotile). **Nephrite**, to which much of the "Jade" used for ornamental purposes belongs, is a compact fibrous variety of tremolite or actinolite. **Uralite**, a name commonly given to fibrous amphiboles resulting from the alteration of rock-forming pyroxenes, is usually actinolite, but may be tremolite or hornblende.

Of the *monoclinic aluminous amphiboles*, by far the most important is **Hornblende**. This mineral is so variable in chemical composition, and so many complex molecules occur in the different varieties, that it is not easy to represent it by a chemical formula. It will be sufficient for our purpose to state that it differs from tremolite and actinolite in containing a notable percentage of alumina, higher percentages of iron oxides and often a considerable content of alkalies. Two varieties are recognised—namely, **Common Hornblende** and **Basaltic Hornblende.** The former is dark leek-green to black in hand specimen, but is green or greenish-brown in transmitted light in thin section. The crystals generally show an elongated prismatic habit, but sometimes appear as blade-like, fibrous, radiating aggregates. It is an essential constituent of many plutonic rocks and is developed in large amount in many crystalline metamorphic rocks. It commonly alters to chlorite, often accompanied by calcite, epidote, quartz, etc., or it may be still further broken up by weathering, and reduced to the condition of a ferruginous clay.

Basaltic Hornblende is generally brownish-black to pitch-black, but when viewed in thin sections it usually shows a deep brown or reddish-brown colour. The crystals are commonly short, stout prisms, and are frequently well formed transverse sections giving typical six-sided outlines showing well the characteristic prism angle and the intersecting cleavages (see Plate IV. 1). The mineral occurs as a macroscopic and microscopic ingredient of certain trachytes, andesites, and basalts—the crystals often showing corroded blackened borders —the result of magmatic "resorption."

The **Soda-amphiboles,** which are highly ferriferous, and some of which are non-aluminous, are important constituents of igneous rocks rich in alkalies, such as the feldspathoid-bearing types. Common varieties include *barkevikite*, *arfvedsonite*, and *riebeckite*. Another, *glaucophane*, is the chief constituent of glaucophane-schist. They cannot be distinguished, as a rule, from common hornblende in hand specimens, but, in thin rock slices the colours and pleochroism are distinctive. The only other amphibole that need be mentioned is **Smaragdite**—a peculiar grass-green fibrous lamellar form. It occurs in eclogite as an alteration-product of the green variety of diopside known as *omphacite.*

THE PYROXENE GROUP

The **Pyroxenes** are metasilicates of magnesium, iron, and calcium alone, or in combination with double silicates of sodium with aluminium or ferric iron. Like the amphiboles they crystallise in both the monoclinic and orthorhombic systems. All pyroxene crystals have good prismatic cleavage in two directions, the cleavage angle being about 87°. They have a hardness of 5 to 7 and a specific gravity of 2·8 to 3·7. Although, as in the case of the amphiboles, the monoclinic varieties have the wider distribution as rock-formers, the orthorhombic types are also of considerable importance.

Monoclinic Pyroxenes.—The *non-aluminous monoclinic pyroxenes* include *Pigeonite* $\{m(Mg, Fe)SiO_3 . nCaMgSi_2O_6\}$ which is found in some gabbros, dolerites and basalts, and *Diopside* $\{Ca(Mg, Fe)Si_2O_6\}$ which is abundant in certain igneous rocks but is more important as a constituent of metamorphic rocks. The chief *aluminous monoclinic pyroxene* is **Augite** $\{CaMgSi_2O_6$ with $(Mg, Fe)(Al, Fe)_2SiO_6\}$, which is particularly abundant in igneous rocks and is an occasional component of crystalline schists. Varieties of augite rich in titanium are widely distributed and are known as *titanaugite.* Common, too, in soda-rich igneous rocks is a soda-augite, *aegirine-augite* which carries a varying content of the *acmite* molecule $(NaFeSi_2O_6)$. The name *diallage* has been given to finely laminated varieties of both diopside and augite.

The monoclinic pyroxenes occur typically as short prismatic crystals. Diopsidic varieties range in colour from white through pale green and deeper green to nearly black; the augites are black. Common alteration-products are chlorite, often accompanied by iron oxides, epidote, quartz and carbonates, uralite, and actinolite.

In thin slices the monoclinic pyroxenes may be colourless, as in the case of many diopsides, or, as in the more ferriferous diopsides and augite the colour may be some shade of green or brown. For the most part they are not pleochroic, but strong pleochroism in green tones is characteristic of ægirine-augite, and, in reddish and violet tones, of titanaugite. The rectangular cleavage is well seen in thin sections, and, where the crystals are euhedral, the eight-sided shape of transverse sections is characteristic (see Plate IV. 2). All show high relief and strong double refraction.

The **Orthorhombic Pyroxenes,** which play a much more important part as rock-formers than the corresponding amphiboles, are all metasilicates of magnesium and iron. They form a continuous isomorphous series called *Enstenite*; varieties with up to 15 per cent. of FeO are known as *Enstatite* $\{(Mg, Fe)SiO_3\}$, the more ferriferous members of the series as *Hypersthene.* The term *Bronzite* has been applied to orthorhombic pyroxenes showing a bronzy or sub-metallic lustre caused by the presence of inclusions. Enstatite is an abundant constituent of peridotites and pyroxenites and it occurs also as a product of contact metamorphism; hypersthene plays an important rôle in the composition of many andesites and it is the chief ferromagnesian constituent of norites, but it is less common in the ultrabasic igneous rocks.

Enstatite is typically green in hand specimens, but may be white, yellow, or brown; hypersthene varies in colour from yellowish-brown to black. Both minerals alter characteristically to a fibrous form of serpentine known as *Bastite.*

In thin slices enstatite is colourless while hypersthene is reddish or greenish with distinct pleochroism. All the orthorhombic pyroxenes show high relief, but, unlike the monoclinic varieties, they give low interference colours because of their weak double refraction.

THE OLIVINE GROUP

The common minerals of this group are all orthosilicates of magnesium and iron. In **Olivine** or **Chrysolite** $\{(Mg, Fe)_2SiO_4\}$ the ratio of magnesium to iron is always very high. Like all the members of the group it crystallises in the orthorhombic system, the crystals being sometimes euhedral, but, more often perhaps, so much rounded by magmatic corrosion that they appear as elliptical granules. Cleavage is usually rather imperfectly developed, but the mineral shows pronounced conchoidal fracture. It is yellowish-green or olive-green in colour and has a vitreous lustre. It has a hardness of 6·5 to 7 and the specific gravity is 3·2 to 3·34. Olivine gelatinises readily under the attack of even weak acids. In many rocks it has undergone complete alteration. The commonest replacement products are serpentine and iron oxides, but in some cases the original olivine is pseudomorphed by a mica-like mineral, bowlingite, in others by hæmatite or limonite. In rocks which are much weathered the alteration-products of the olivine include much calcite and other carbonates, opal and quartz. When fresh it is easily distinguished from its associated minerals by its green colour, glassy lustre and conchoidal fracture. Olivine is a constituent of the majority of basic and ultrabasic igneous rocks; in one of the latter, dunite, it is the only essential mineral, and it is the chief component of the "olivine nodules" found in many basaltic rocks. *Forsterite* (Mg_2SiO_4) is a characteristic mineral in marbles which have been formed by the contact metamorphism of sandy dolomites; *Fayalite* (Fe_2SiO_4) occurs chiefly in acid and intermediate rocks relatively poor in magnesia, as in some pegmatites, rhyolites, pitchstones and trachytes. The finely coloured (yellow and green) and highly transparent varieties of olivine used in jewellery are known as *Peridote.*

In thin slices olivine is colourless to pale green and is not pleochroic. The lozenge-shaped outlines of longitudinal sections of euhedral crystals are characteristic (see Plate IV. 4). The high relief and shagreened surface, the curving cracks and the very strong double refraction are also features of diagnostic value. When the olivine has been completely serpentinised it shows distinctive "mesh-structure" owing to the fact that separated grains of magnetite, following the original curving lines of fracture and the lines of imperfect cleavage, give an appearance like the meshes of a net (see Plate XVI. 3).

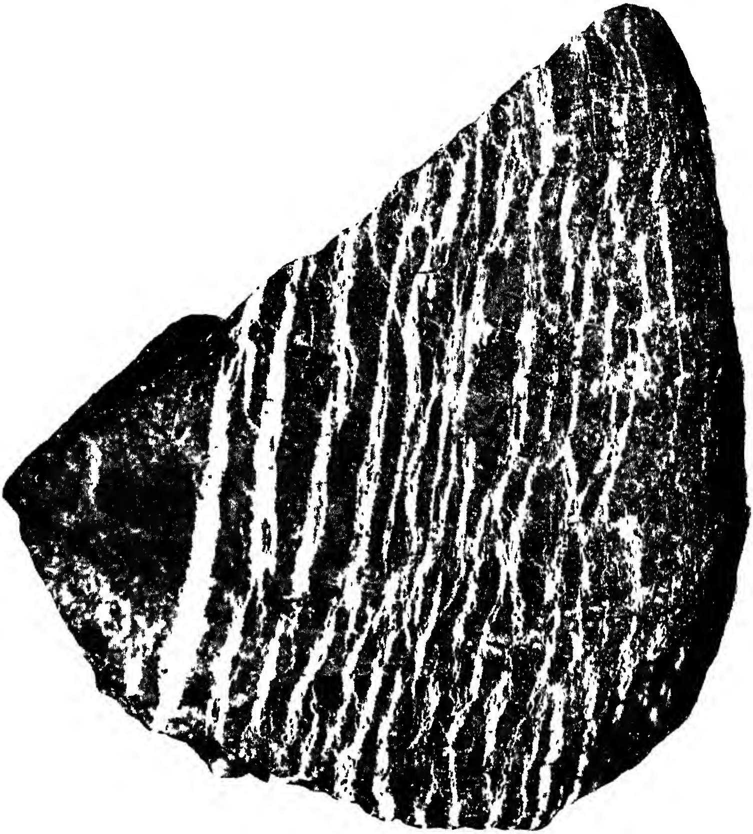
THE CHLORITE GROUP

Under this head are included certain greenish-coloured minerals which are composed mainly of hydrated silicates of aluminium, with ferrous iron and magnesium. Where chromium replaces part of the aluminium they are pink in colour. As rock-formers **Chlorites** occur in the form of pseudo-hexagonal non-elastic plates, but most frequently as bent and irregularly bounded scales, tufts, and fibres, or as scaly or earthy aggregates. Often they somewhat resemble micas. The hardness is 2 to 3, and the specific gravity 2·6 to 3·0. The only rock largely composed of these minerals is chlorite-schist. They occur frequently, however, in eruptive rocks as secondary products, from the alteration of such minerals as hornblende, augite, biotite, etc. Many igneous rocks, indeed, owe their greenish colour to the alteration of their original ferro-magnesian constituents into "chlorite." In thin slices the chlorites are usually pale green in colour and feebly pleochroic. They have low relief and weak birefringence.

THE TALC AND SERPENTINE GROUP

Talc $\{H_2Mg_3(SiO_3)_4\}$—a hydrous silicate of magnesium—is a white or pale greenish mineral, readily cleavable into non-elastic folia, and so soft that it can be scratched with the finger-nail. Hardness = 1, specific gravity = 2·7 to 2·8. It has a pearly lustre and a pronounced greasy feel. It occurs usually in compact foliated masses, very rarely in tabular orthorhombic (?) crystals. In igneous rocks it is seldom found, and always as a secondary product, usually in the form of foliated plates and scales, replacing non-aluminous magnesian silicates. It is met with chiefly in the crystalline schists, being the dominant ingredient of talc-schist.

Steatite (soap-stone) is a cryptocrystalline to compact variety of talc. *Potstone* is a similar but very impure variety. *Sepiolite* or *Meerschaum* is a closely allied mineral of nearly the same chemical composition. It is



Serpentine veined with Chrysotile. Natural size.

amorphous, occurring in irregularly shaped nodules and masses, which are compact and finely porous. When dry it floats in water, which it absorbs greedily. Like talc, it is eminently a product of the alteration of magnesian silicates. As a rock-former it is of no importance.

Serpentine ($H_4Mg_3Si_2O_9$)—a hydrous silicate of magnesium, with part of the magnesium often replaced by iron—occurs in compact or granular masses and in aggregates with a lamellar, scaly, or fibrous structure. It is not infrequently pseudomorphous after other crystallised minerals such as olivine. The colour is some dark shade of green, red, or yellow, often mottled or variegated. It has a hardness of 3 to 4 and its specific gravity is 2·5 to 2·7. It has a smooth feel and usually a feeble lustre. The finely fibrous variety is known as *Chrysotile* (see Plate V.). This mineral can be distinguished from the common chlorites in thin section by its stronger birefringence. Most of the "asbestos" of commerce is not true asbestos, but chrysotile. Common "serpentine" consists largely of a lamellar variety, *antigorite*, which is difficult to distinguish in thin slices from the ordinary chlorites, with which, indeed, it is included by some authors. It is the most frequent alteration-product of the olivines, and sometimes replaces the pyroxenes and amphiboles, of basic and ultrabasic igneous rocks. It is the chief constituent of the rock serpentine. *Noble Serpentine* is a pure variety of a uniform colour (green or yellow), which takes on a fine polish, and is used as an ornamental stone.

THE GLAUCONITE GROUP

Glauconite, a hydrous silicate of aluminium, potassium, and iron, occurs in granules with microcrystalline structure. It is dull green in colour and in thin slices is pleochroic in shades varying from straw-yellow to green and yellowish-green. It has a hardness of 2 and the specific gravity is 2·2 to 2·8. Glauconite is a common constituent of sands accumulating near the continental shores at depths of from 600 to 5000 feet, and has been noted in marine sandstones belonging to many geological periods. It is particularly abundant in the "green sands" of the Cretaceous system. **Celadonite** is similar in composition. It is an alteration-product of the ferromagnesian silicates of basic lavas, and is found not infrequently in amygdales in such rocks. Related to glauconite also is *greenalite,* a green hydrated silicate of iron, found as granules in the cherts associated with the iron ores of the Lake Superior region.

THE EPIDOTE GROUP

The principal rock-forming member of this group is **Pistacite,** or iron-epidote—so called to distinguish it from *Zoisite,* or lime-epidote. Pistacite

$\{HCa_2(Al, Fe)_3Si_3O_{13}\}$ occurs crystallised in monoclinic forms, or appears in finely granular masses of a peculiar pistachio-green colour. The hardness is from 6 to 7 and the specific gravity 3·37 to 3·5. The mineral fuses with difficulty before the blowpipe, and is partially decomposed by hydrochloric acid. It is met with frequently as a constituent of schistose rocks (epidote-gneiss, epidote-amphibolite), and as a "contact mineral" in limestones, etc., which have been affected by the intrusion of igneous rock. It is a common alteration-product in eruptive-rocks, replacing such minerals as hornblende, biotite, feldspars, etc., and often associated with chlorite. In thin slices it has very high relief and gives brilliant interference colours, often variable within a single crystal. The lemon yellow tones in its pleochroism scheme are often distinctive. **Zoisite** (orthorhombic) is a silicate of calcium and aluminium, met with not infrequently in schistose rocks and as an alteration-product of the feldspars of igneous rocks. *Clinozoisite* is a monoclinic epidote containing little iron and approaching zoisite in composition.

THE GARNET GROUP

Garnets are silicates of aluminium, iron, calcium, magnesium, chromium, and manganese, usually only two or three of these being abundantly present. According to the dominance of the chief constituents, we have iron-, calcium-, magnesium-, manganese-aluminium garnets, etc. They usually assume dodecahedral (see Plate I. 3) or icositetrahedral forms, and have no cleavage. The hardness is 6·5 to 7·5 and the specific gravity 3·4 to 4·3. The lustre is greasy or resinous. Common rock-forming iron-aluminium garnet (*Almandine*, $Fe_3Al_2Si_3O_{12}$) is generally some shade of red—hyacinth to reddish-brown. It is fusible before the blowpipe, but is not readily decomposed by acids. In nature it alters chiefly to chlorite, and sometimes to serpentine, epidote, etc. Under the microscope its sections are rounded or many-sided (see Plate VI. 2); it shows no cleavage but only irregular cracks, not infrequently lined with decomposition-products. Enclosures often abound. Owing to its high refractive index garnet stands out in strong relief in thin section; it usually remains dark when rotated between crossed nicols, but sometimes shows anomalous weak double refraction. It is common in many schists, is an essential constituent of eclogite and garnet-rocks, and occasionally occurs in granite and quartz-porphyry. Calcium-aluminium garnet (*Grossularite*, $Ca_3Al_2Si_3O_{12}$) is often present as a "contact mineral" in metamorphosed limestone. The clear, finely coloured varieties of garnet have some value as gems; amongst these are *Almandine* and *Pyrope* ($Mg_3Al_2Si_3O_{12}$), the former occurring in schists and granite, the latter in peridotites and serpentine. *Melanite*, a black calcium-iron-titanium garnet, is met with in nepheline-syenites, phonolites, basanites, etc.

THE ZIRCON GROUP

The only rock-former in this group is **Zircon** ($ZrSiO_4$), which appears mostly in the form of small, brown tetragonal crystals enclosed in other minerals. Although only sparingly present it has a wide distribution, occurring in eruptive rocks of all kinds (but not often in the basic kinds), as well as in crystalline schists, especially in gneiss. Larger crystals are found in some syenites. Zircon is not readily decomposed, and is thus often met with in quartz sands which have been derived from the disintegration of rocks in which it occurs as a primary constituent. The mineral is harder and heavier than rutile—the hardness being 7·5 and the specific gravity 4·66 to 4·7. Under the microscope it is distinguished by its very high refractive index and extremely strong double refraction. When enclosed in certain minerals, in particular biotite, zircons are surrounded by "pleochroic halos." Clear, transparent varieties, such as *Hyacinth* and *Jargon*, are valued as gems.

TITANITE

Titanite or **Sphene** ($CaTiSiO_5$) is a widely distributed accessory ingredient of eruptive rocks (especially of hornblendic granite, syenite, diorite, etc.), and occurs also in certain schistose rocks and crystalline limestones. It crystallises in monoclinic forms, which are usually lozenge- or wedge-shaped (see Plate VI. 1). It is decomposed by sulphuric and hydrofluoric acids, and fuses with difficulty. Its hardness is 5 to 5·5 and its specific gravity 3·4 to 3·56. Its colour is yellowish to brown. Well-formed crystals often appear in the drusy cavities of granite, in gneiss, and in metamorphosed limestones. As an accessory ingredient of eruptive rocks it is usually of microscopic size. *Leucoxene*, a dull white or grey earthy form of titanite, occurs as an alteration-product of ilmenite and titanomagnetite in basic igneous rocks. In thin slices sphene may be recognised by the characteristic wedge-shaped sections, by its extremely high relief and very strong birefringence.

THE TOURMALINE GROUP

Tourmaline crystallises in trigonal (hemimorphic) forms. It has a complicated and variable chemical composition, but is essentially a borosilicate of aluminium, with magnesium, iron, alkalies, fluorine, and basic water. Its hardness is 7 to 7·5 and specific gravity 2·98 to 3·20. It is not attacked by acids, but is fusible, the degree of fusibility varying with the chemical composition. The only form of any importance as a rock-constituent is the black variety, **Schorl**, which often occurs as long trigonal prisms longitudinally striated; it appears also as microscopic prisms and grains, or as groups of acicular crystals with a radiated arrangement (see Plate X. 2); occasionally it is met with as massive aggregates. It varies from very dark green to black. The cleavage is indistinct, and this, with its greater hardness and the form of the prisms, serves to distinguish schorl from hornblende. It is often a constituent of schistose rocks, and not infrequently an ingredient of acid plutonic rocks, especially granite. It occurs commonly as a "contact mineral" in the zone of altered rocks surrounding granite, etc. The mineral does not weather readily. The transparent, beautifully coloured tourmalines are in some request for jewellery.

THE ANDALUSITE GROUP

These are silicates of aluminium, crystallising in orthorhombic and triclinic forms, and occurring chiefly in crystalline schists and in argillaceous rocks which have been affected by the action of intrusive masses. The members of the group of most frequent occurrence as rock-formers are *Andalusite* (with its variety *Chiastolite*), *Sillimanite*, *Kyanite* (all having the composition Al_2SiO_5), and *Staurolite* ($H_2FeAl_4Si_2O_{12}$).

Andalusite occurs not infrequently as well-developed columnar prisms (rhombic but nearly rectangular) in mica-schist and gneiss, and is often a notable ingredient of the hornfelsed argillaceous rocks surrounding granites. Hardness 7·5; specific gravity 3·1 to 3·2. It is often more or less crowded with carbonaceous inclusions; and, when these are regularly arranged so as, in cross-sections of the prism, to show a cruciform or tesselated pattern, we have the variety known as *Chiastolite* (see Plate VI. 3). **Sillimanite** sometimes called *Fibrolite*, assumes the form of thin rod-like or needle-like orthorhombic prisms, occurring rarely in igneous rocks which have absorbed clay rocks, but met with chiefly in high temperature zones of contact metamorphism, in xenoliths and in crystalline schists (see Plate VI. 2, 4). **Kyanite** is a white or pale blue mineral, crystallising in long broad flattened prisms (triclinic), and occurring in certain crystalline schists, but never in igneous rocks. A remarkable character of kyanite is its hardness, which is not the same in different directions; along the broad lateral planes it is only 4·5, while across these it is 7. It is often associated with garnet and **Staurolite** —the latter being a dark brownish-red mineral which assumes the form of short and thick or long and broad columnar crystals (orthorhombic). Interpenetrating cruciform twins of staurolite are very common. It does not occur in eruptive rocks.

CORDIERITE.

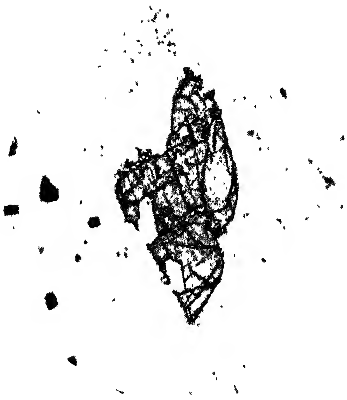
The composition of **Cordierite** (*Dichroite*, *Iolite*) is given by the formula $Mg_2Al_4Si_5O_{18}$. Varieties containing some iron are, however, not uncommon. It crystallises in the orthorhombic system, but a development of cyclic twinning often leads to the production of short pseudohexagonal prisms. The colour in hand specimens is usually some shade of blue and thick fragments are strongly pleochroic. The lustre is vitreous. The mineral has a hardness of 7 to 7·5 and its specific gravity is 2·57 to 2·66. It alters to a variety of minerals, chiefly muscovite, biotite and chlorite. In thin slices it shows low relief and weak double refraction, but can be distinguished from the quartz and orthoclase with which it is associated by its mode of alteration and by the presence of yellow pleochroic halos round minute inclusions of zircon (see Plate VI. 4). Cordierite is found chiefly in gneisses and crystalline schists and in hornfelses in zones of contact metamorphism. It is of infrequent occurrence in igneous rocks.

THE ZEOLITE GROUP

The **Zeolites** are a group of hydrous silicates of aluminium with sodium and calcium, or rarely barium and strontium. The water they contain is easily driven off before the blowpipe. Although they occur occasionally as primary minerals in igneous rocks, they are for the most part secondary in origin, formed by the hydration chiefly of feldspars and feldspathoids. Their most conspicuous modes of occurrence are as infillings of vesicular

PLATE VI

Microscopic Structure of Minerals and Rocks



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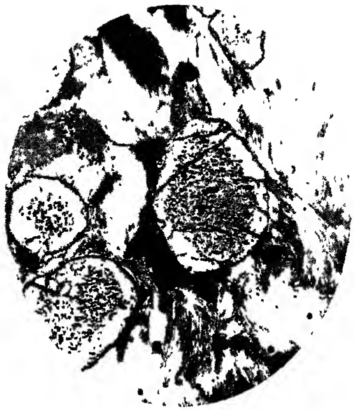

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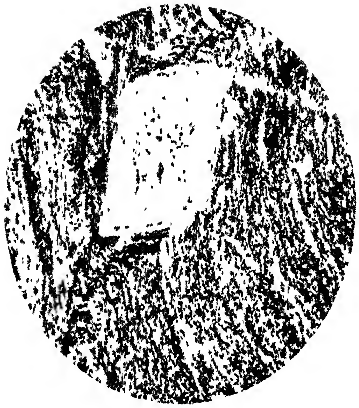

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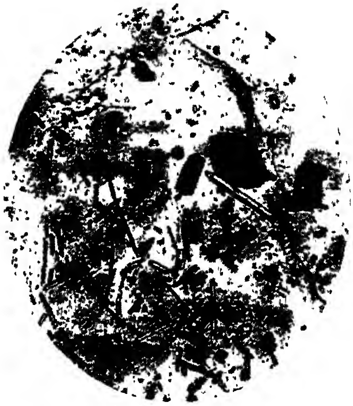

4.

1. Sphene, wedge-shaped, with included apatites, enclosed in feldspar Hornblende-syenite, Dresden. × 20.
2. Garnets, showing high relief; minute needles of sillimanite (fibrolite) enclosed in quartz on right and in muscovite at bottom. Gneiss, near margin of Criffel granite mass. × 35.
3. Chiastolite crystal with graphitic inclusions Chiastolite-slate, Fichtelgebirge. × 20.
4. Cordierite with inclusions of sillimanite (needles), biotite (black), and small zircons showing halos. Sillimanite-cordierite-gneiss. × 80.

cavities and as veins in basic igneous rocks. Sometimes they are grouped in crystal aggregates, but very often they are found massive with internal radiated fibrous structure. Most of the zeolites are white or colourless. Their hardness ranges from 3·5 to 5·5 and their specific gravity from 2·0 to 2·7. They are readily decomposed by acids, usually with gelatinisation. They appear in rock slices generally as radiating groups of crystalline fibres, often pseudomorphous after feldspars and feldspathoids. They are characterised by very low refringence and consequent negative low relief; nearly all give very low interference colours—thomsonite is a noteworthy exception. Among the commonly occurring varieties are: *Natrolite*, *Heulandite*, *Stilbite*, *Chabazite*, and *Thomsonite*.

THE KAOLIN GROUP

Various decomposition-products are included under the term kaolin, of which much the most important is the hydrated silicate of alumina—**Kaolinite** ($H_4Al_2Si_2O_9$). When pure this mineral is usually white, earthy, or mealy. Occasionally, under the microscope, this white powder may be seen to consist largely or entirely of minute transparent or translucent plates, with pseudo-hexagonal symmetry. Before the blowpipe it is infusible. It is insoluble in acids. Hardness = 2 to 2·5; specific gravity = 2·5. It is a common alteration-product of many rock-forming aluminous silicates, notably the feldspars. When moistened with water it is usually highly plastic. Impurities are commonly present, particularly iron-oxides, which give it a yellow, red, or brown colour; other colours met with are grey, blue, and green. *Lithomarge* is merely an impure compact kaolin; it is often mottled red owing to the presence of ferric hydrate.

III. HALOIDS

Fluor-spar or **Fluorite** (CaF_2) occurs occasionally as an accessory mineral in granites and other acid igneous rocks and as a product of sublimation in volcanic rocks. Very rarely it forms the cementing material of sandstones. It is met with most frequently, however, as veins, especially in the neighbourhood of granite masses or as a gangue-mineral in lodes, particularly in association with lead and tin-ores. The common form of the crystallised mineral is the cube, and interpenetrating twins often occur. The colour is variable—violet, blue, green, yellow, and occasionally pink. The crystals show perfect octahedral cleavage. The mineral has a hardness of 4 and a specific gravity of 3·2. It is soluble in sulphuric acid with evolution of HF.

Rock-salt (NaCl) crystallises in the form of cubes with perfect cubic cleavage. It has hardness 2·5 and specific gravity 2·17. It is soluble in water and has a saline taste. It may be colourless or white, also yellowish, reddish, or blue. It is met with in extensive beds, sometimes of great thickness, in rocks of various ages in association with gypsum, anhydrite, clay, sandstone, etc. Occasionally it is found as a sublimation product in volcanic regions, and, in arid districts, it occurs as a surface efflorescence.

IV. SULPHIDES

Pyrite (FeS_2) commonly crystallises in cubes, pyritohedra and octahedra, but not infrequently occurs as irregular aggregates. It has a very uniform, brass-yellow colour and metallic lustre. Hardness = 6 to 6·5 ; specific gravity = 5·02 ; streak = black. It is decomposed by nitric acid but is insoluble in hydrochloric acid. The only minerals with which pyrite might possibly be confounded are chalcopyrite ($CuFeS_2$), magnetic pyrite $\{FeS(+S)\}$, and perhaps gold. Gold, however, is malleable, and the others are not. Pyrite is paler and considerably harder (6 to 6·5) than chalcopyrite (3·5 to 4) ; the streak of the former is black, while that of the latter is greenish-black. *Magnetic Pyrite* or *Pyrrhotite* (an iron-sulphide of variable composition, containing sometimes as much as 5 per cent. of nickel) has a characteristic pinchbeck-bronze colour, is slightly magnetic, and not so hard as pyrite, while the streak is greyish-black. Pyrite often occurs in the form of detached crystals and aggregates in clay-slate. It is an occasional ingredient of schistose rocks, sandstone, coals, and argillaceous rocks of various kinds, often as fine-grained impregnations. Now and again it appears as an accessory mineral in eruptive rocks. It is of frequent occurrence also in lodes, either as crystal aggregates or massive. Pyrrhotite is not so common a rock-former as pyrite. Occasionally it is present in basic igneous rocks (gabbro, basalt, etc.) and schists (amphibole rocks). Like pyrite, it often occurs in metalliferous veins—the two minerals being not infrequently associated in the so-called "bedded veins" or "quasi-bedded ore formations."

Marcasite is an orthorhombic mineral, having the same composition as pyrite. It occurs usually compact or cryptocrystalline, and is often disseminated in minute grains through certain sedimentary rocks. Radiated nodular forms are also very common. The hardness is the same as that of pyrite, and the specific gravity slightly less. It is a less stable form than pyrite. The colour is pale brass-yellow, inclined often to green or grey. It has hardly so wide a distribution as pyrite, occurring chiefly as concretions in argillaceous and calcareous rocks.

V. CARBONATES

Calcite or **Calc-spar** ($CaCO_3$) crystallises in the trigonal system, and assumes a great variety of crystalline habit. The cleavage is rhombohedral, as exemplified by the well-known transparent Iceland spar, so commonly used for polarising instruments, but the unit rhombohedron is a rare crystal. Scalenohedral forms are very common, as in dog-tooth spar. Calcite is recognised by its slight hardness (= 3), as it is easily scratched with the penknife, by the readiness with which it effervesces briskly with cold dilute hydrochloric acid, and by its perfect rhombohedral cleavage. The specific gravity is 2·6 to 2·8. Calcite is an important constituent of many aqueous deposits—as limestone, calc-sinter, etc. It is a frequent binding material in sedimentary rocks, and is the most important ingredient of marbles. As a secondary product, it appears commonly in the minute pores and capillaries of many different minerals and rocks; it also occupies cracks, fissures, and cavities of all kinds—being a common gangue-mineral in lodes. It is the chief petrifying agent, and, next to quartz, the commonest of all minerals.

Aragonite has the same composition as calcite, but crystallises in the orthorhombic system. Its greater specific gravity (2·9 to 3) and the relatively imperfect nature of the cleavage, which is parallel to the length of the crystals, may be used to distinguish this mineral from calcite. It is a more soluble form of calcium-carbonate than calcite, and not nearly so common as that mineral. Sometimes it is met with in beds associated with gypsum and iron-ore, and not infrequently in cracks and cavities in recent eruptive rocks. It is often a deposition from hot springs.

Dolomite or **Bitter Spar** ($CaMg(CO_3)_2$) crystallises in the trigonal system—the faces of the crystals being frequently curved. Like calcite it has perfect rhombohedral cleavage. Crystals of dolomite often show characteristic pearly lustre, and hence the mineral is sometimes termed "pearl spar." Hardness = 3·5 to 4; specific gravity = 2·8 to 2·9. It is only slightly affected by cold dilute hydrochloric acid, but is dissolved when the acid is heated. It may be variously coloured, but white and yellow varieties are most common. Magnesian limestone is composed in large part of this mineral.

Siderite or **Chalybite** ($FeCO_3$) occurs usually in rhombohedral forms, often with curved faces, and has perfect rhombohedral cleavage. It is colourless or pale yellow when freshly exposed, but soon becomes tarnished brown or rusty. Hardness = 3·5 to 4; specific gravity = 3·83 to 3·88; the mineral is infusible before the blowpipe, but effervesces with weak acids. It occurs in lodes along with various ores. *Sphærosiderite* is the name given to a compact siderite often showing a concentric, radiating, fibrous structure. It occurs as nodules and nodular masses in veins and cavities in basalt, etc. *Clay-ironstone* is an impure variety of sphærosiderite mixed with clay, which occurs as nodules, bands, and beds in various geological formations. *Blackband-ironstone* is a clay-ironstone containing a notable amount of carbonaceous matter. [Clay-ironstone and blackband-ironstone are rather rocks than minerals.]

VI. SULPHATES

Anhydrite ($CaSO_4$) crystallises in the orthorhombic system, but usually occurs massive or in granular and fibrous aggregates. It cleaves in three directions at right angles (pseudo-cubic). It is often associated with rock-salt and gypsum. Hardness = 3 to 3·5; specific gravity = 2·9 to 3. It is soluble in hydrochloric acid, and fuses before the blowpipe with difficulty to a white enamel, colouring the flame reddish-yellow.

Gypsum ($CaSO_4.2H_2O$) crystallises in monoclinic forms—the crystals being often twinned as, for example, in the familiar "swallow-tail" twins. Its hardness (1·5 to 2) and specific gravity (2·3) are considerably less than those of anhydrite. It may be variously coloured, but is usually transparent or white. It is soluble in hydrochloric acid. Before the blowpipe it becomes opaque or white, exfoliates, and fuses to a white enamel. Crystals, lenticular concretions, and interrupted layers of gypsum often occur in clays. Frequently it appears as granular and compact masses, arranged as layers and thick beds, where it is commonly associated with rock-salt and anhydrite. Now and again it forms the cement or binding material of sandstone. *Selenite* is the name given to crystallised gypsum; it shows perfect cleavage—the laminæ being flexible but not elastic. The very fine-grained cryptocrystalline kinds are usually termed *Alabaster*, and the fibrous varieties *Satin Spar*.

Barytes or **Heavy Spar** ($BaSO_4$) crystallises in the orthorhombic system. Fibrous varieties are common. It has not a wide range as a rock-forming mineral, occurring rarely as the cementing material of sandstones and more often as a secondary mineral in veins and other cavities. It is commonly associated with ores (especially sulphides) in lodes. Its hardness (2·5 to 3·5) is near that of calcite, but its greater specific gravity (4·3 to 4·6) and its resistance to acids at once distinguish it from the latter. Barytes decrepitates and fuses with difficulty before the blowpipe, colouring the flame yellowish-green.

VII. PHOSPHATES

Apatite {$Ca_5(F, Cl)P_3O_{12}$} is the only phosphate which is a rock-forming mineral. Common apatite is a *fluor-apatite*, with very little chlorine. This mineral crystallises in the hexagonal system, usually as six-sided prisms. Its colour is usually sea-green to bluish-green, but brown, reddish, and yellow tints are also common; its lustre is vitreous to resinous. Hardness = 5; specific gravity = 3·16 to 3·22. It is soluble in hydrochloric acid and fusible with difficulty before the blowpipe. In thin slices it is colourless, with high relief and very low interference colours. It occurs as a frequent but usually a microscopic accessory ingredient of very many eruptive rocks and crystalline schists, commonly in the form of long, slender, hexagonal prisms or needles (see Plate II. 4). It is a frequent inclusion in all the essential constituents of eruptive rocks. Next to magnetite, it has the widest distribution of all accessory rock-constituents. Large crystals occur in the drusy cavities of some granites and in pegmatites. It is met with also as irregular layers (often associated with magnetite) among schistose rocks; while crystals, large and small, not infrequently appear in talc- and chlorite-schists, and in metamorphosed limestones. Again, it forms independent veins of large size, associated with gabbro. The earthy and concretionary varieties of phosphate of lime are known as *Phosphorite*—and many of these are of organic origin.

VIII. ELEMENTS

Carbon, in the form of **Graphite,** is the only element which plays a relatively considerable part as a rock-former. Graphite is usually not crystallised, but sometimes it appears as flat, six-sided plates. Hardness = 1; specific gravity = 2. It is dark grey to black in colour, with an almost metallic lustre; has a greasy feel; and yields a black and shining streak. It is not affected by acids. It occurs as a constituent (sparingly or abundantly, as the case may be) of many schistose rocks and slates, as in graphite-schist, graphite-gneiss. Now and again lenticular beds of it appear among schists, and not infrequently it occupies veins and other cavities traversing such rocks. It has been met with also in granite and basalt. Coal is sometimes converted into graphite by contact with eruptive rock, as at New Cumnock and near Shotts, in Scotland.

Many minerals and rocks are rendered dark or even black owing to the quantity of carbonaceous matter they contain. When the carbonaceous matter is quite amorphous (*i.e.* destitute of crystalline form and structure) it is readily driven off by heating. Pure graphite, however, burns only with the greatest difficulty before the blowpipe.

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CHAPTER III

ROCKS

Classification:—Crystalline Igneous Rocks—their general characters. Chief Minerals of Igneous Rocks. Primary and Secondary Minerals. Groups of Igneous Rocks:—Feldspathic Rocks with abundant Quartz; Feldspathic Rocks, free from or poor in Quartz or Feldspathoids; Feldspathic Rocks with abundant Feldspathoids; Feldspathoidal Rocks, free from or poor in Feldspars; Rocks without essential Feldspars or Feldspathoids. Pyroclastic Rocks.

THE term "rock," as used by the geologist, means any mass or aggregate of one or more kinds of mineral or of organic matter, whether hard and consolidated or soft and incoherent, which owes its origin to the operation of natural causes. Thus granite, basalt, limestone, clay, sand, silt, and peat are all equally termed rocks.

Speaking generally, we may say that the unconsolidated rocks occupy for the most part a superficial position—overspreading and concealing the consolidated rocks of which the earth's crust is chiefly composed. There are many exceptions to this rule, however. Sometimes, for example, unconsolidated materials occur at considerable depths from the surface, buried under masses of hard rock. Nor is the relative age of a rock always indicated by the degree of its consolidation. Many incoherent rocks are of great geological antiquity; while, on the other hand, some rocks of quite recent age are nevertheless as hard and resistant as the oldest.

Classification of Rocks.—The rocks of which the earth's crust is constructed are very diverse in character and origin. Some owe their origin to eruptive and volcanic forces; others are obviously composed of materials which have been derived from the disintegration of pre-existing rock-masses; while yet others have undergone certain more or less fundamental changes since the time of their formation, so that it is not always possible to tell what their original character may have been. We have thus three more or less well-marked types of rocks, which may be designated **Igneous, Derivative,** and **Metamorphic** respectively.

I. IGNEOUS ROCKS

This division includes all rocks which owe their origin to the operation of eruptive and volcanic forces. Some consist either wholly or in part of crystalline ingredients, while others are composed of fragmental materials. Hence we have two groups, viz.: A. **Crystalline,** and B. **Fragmental** or **Clastic Igneous Rocks.**

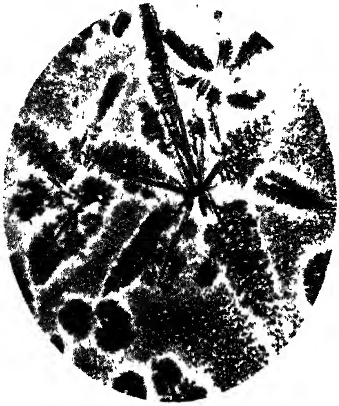
A. Crystalline Igneous Rocks

These rocks, which have all consolidated from a state of igneous fusion, present considerable diversity in mineral composition and texture. The essential minerals, however, belong always to one or another of quite a small series of mineral groups, and the rocks consist mainly of varying associations of quartz, feldspars, feldspathoids, micas, amphiboles, pyroxenes and olivines. The textural characters, which depend on the size and shape of the component crystals and the mode of arrangement of these with respect to one another and to any undifferentiated glassy base, have been determined by a number of factors. The dominant factor in most cases has been the rate of cooling of the silicate solution, but the texture is dependent also on the viscosity of the solution, since high viscosity retards the growth of crystals, and on the presence of volatile constituents which act as "mineralisers," promote the fluidity of the solution and stimulate crystal growth. Under favourable conditions all the constituents appear as crystals; sometimes the rock consists of a mixture of crystalline ingredients and glassy or poorly-differentiated base; or, cooling and consolidation may have been so sudden that no crystals can be formed before the solution has congealed to form a vitreous rock. Every gradation is found from coarse pegmatites in which individual crystals may attain a length of many feet to rocks which appear to be completely glassy. Traces of incipient crystallisation, however, are rarely absent when such glasses are examined under the microscope, and all the types, for purposes of description, may be classed as crystalline igneous rocks.

The texture of these rocks may be more or less even-

PLATE VII

Microscopic Structure of Minerals and Rocks



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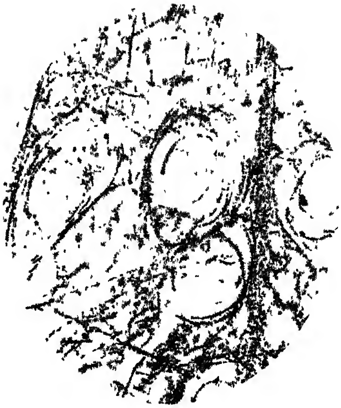

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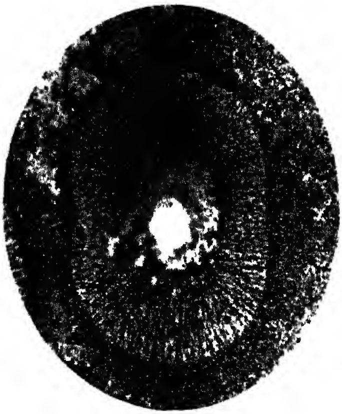

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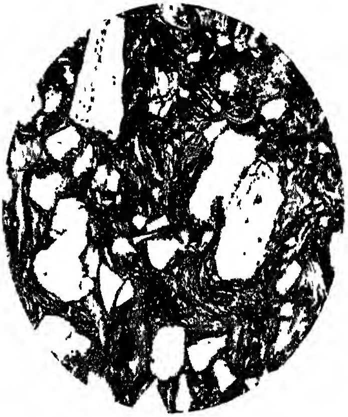


4.

1. Microlites (arborescent groups of) and crystallites in glass. Pitchstone, Corriegills, Arran × 80.
2. Perlitic structure. Pitchstone, Corbitz, Meissen. × 20.
3. Spherulite in felsite. × 20.
4. Phenocrysts of feldspars, quartz and hypersthene in glassy groundmass, which shows fluxion structure. Obsidian, Auer on the Etsch, Tyrol. × 20.

[*To face page* 35

grained, or larger crystals may be set in a fine-grained groundmass. In the latter case the large crystals are termed *phenocrysts* and the texture is said to be *porphyritic* (see Plate XI. 1). Individual crystals which are completely bounded by their own crystal faces—as, for example, many phenocrysts,—are termed *idiomorphic* or *euhedral*; those which are bounded in part by their own faces, in part by other crystals, are *hypidiomorphic* or *subhedral*; crystals which are limited in all directions by other crystals are *xenomorphic* or *anhedral*.

When their textural variations are studied in hand specimens crystalline igneous rocks fall readily into two groups:—(*a*) *Phanerocrystalline*—those which are obviously completely crystalline; and (*b*) *Aphanitic*—those where naked-eye determination is insufficient for decision as to whether or not the rock is completely crystalline. The aphanitic rocks, which may or may not show megascopic crystals, include types in which the compact "groundmass" is *lithoidal* or *stony* and others in which it is *vitreous* or *glassy*.

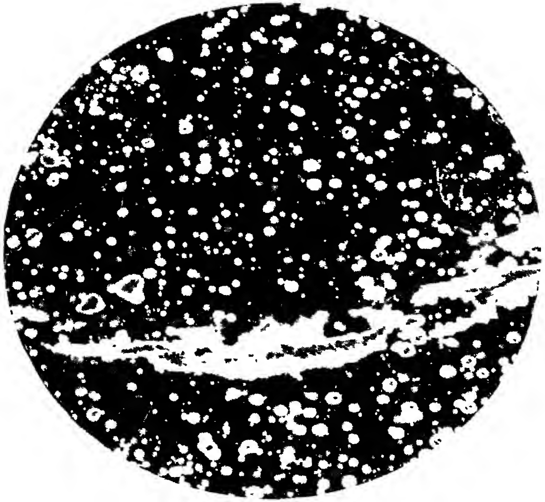
Vitreous Aphanitic Rocks.—*Their General Characters.* Many of these appear to the unassisted eye to be smoothly homogeneous and to contain no trace of crystalline ingredients. They resemble indeed artificial glass. Some have vitreous lustre, in others the lustre is resinous or pitch-like. It is only rarely that microscopic examination of thin slices fails to reveal in such glasses minute rudimentary crystal bodies, which are of two sorts—*crystallites*, which do not react with polarised light and, as a rule, give no hint as to the nature of the mineral to which they belong, and *microlites* (see Plate VII. 1), which represent a more advanced stage and the mineral character of which can usually be determined. A further stage in crystal development is shown by *skeleton crystals* which appear as branching forms or as hollow, imperfectly formed and incomplete crystals. Of frequent occurrence, too, particularly in acid glasses, are *spherulites* (see Plate VIII 1.), roughly spherical bodies, usually the size of a pea or smaller, although much larger examples have been described. They show an internal divergent radiating structure and consist mainly of intergrowths of feldspar and quartz. Spherulites have been regarded as due to rapid growth of microlites in a quickly cooling magma. Similar spherical bodies, sometimes larger than hazel-nuts, are now and then developed in artificial glass. Glassy rocks sometimes contain small enamel-like globules, which, in thin sections, exhibit imperfectly developed concentric cracks, giving what is termed *perlitic* structure (see Plate VII. 2). These structures, which are caused by the strain set up on quick cooling, have been imitated by cooling Canada balsam very rapidly on ground-glass slips. Spherulites may occur sporadically or be closely packed in groups; and, similarly, perlitic structure may be sparsely or abundantly developed. Some glassy rocks, indeed, appear as if composed entirely of enamel-like globules, and vitreous rocks having this character have been called *Perlites*. Besides the rudimentary crystal bodies mentioned above glassy rocks may contain small crystals of microscopic dimensions, and, not infrequently, they are porphyritic owing to the presence of larger megascopic phenocrysts.

There are certain other structures which, although not confined to vitreous rocks, are nevertheless more or less characteristic of these. Frequently, under the microscope, the crystallites, microlites, and small crystals in a glass are seen to have a parallel orientation ; and, very often, too, a glassy rock shows in hand specimens a ribboned or striped appearance, darker and lighter layers rudely alternating. Such structures, which are due obviously to differential movement of the rock while it was still in a mobile condition, are known as *fluxion* or *fluidal* structures (see Plate VIII. 2). All molten masses contain steam and other gases, which are given off in dense clouds from a lava at the time of its eruption. So long as the lava is very liquid the steam readily escapes ; but as the mass on cooling becomes more viscous the vapours are less easily got rid of. They segregate and expand, pushing the plastic rock aside and thus forming spherical cavities. In this way the upper portion of a lava is often rendered more or less vesicular. As the lava flows on its way the spherical cavities become drawn out in the direction of movement. The vesicles vary in size from mere pores up to cavities more than a foot across, but the larger cavities occur only sporadically. In the case of vitreous rocks the vesicles are rarely large. Often they are so small and so abundant that they may occupy fully as much space as the solid portion which contains them. Vitreous rock of this kind has a spongy, froth-like appearance and is known as *Pumice*.

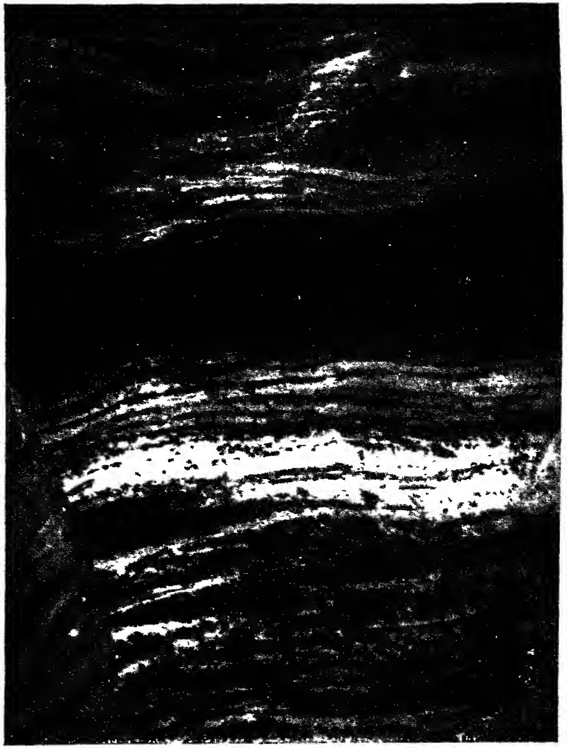
Lithoidal Aphanitic Rocks. *Their General Characters.*—Rocks of this group are occasionally non-porphyritic, but in the majority of cases crystallisation has taken place in two stages, and they are typically porphyritic. Their distinctive characteristic lies in the nature of the groundmass which, in hand specimens, has a stony as opposed to the glassy appearance of vitreous rocks. The groundmass, moreover, is so compact and fine-grained that it is impossible to decide by hand specimen examination alone whether it is or is not completely crystalline. Such rocks have consolidated on or near the surface of the earth. The phenocrysts have formed while the magma was still at some considerable depth and often have attained a relatively large size. They are sometimes euhedral, but not infrequently their corroded outlines show that they have undergone partial resorption, in most cases possibly because of disturbance of chemical equilibrium through changes of temperature and pressure as the still fluid portion of the magma carried them upwards towards the surface. Not only are the phenocrysts frequently corroded, but they have often been broken as a result of corrosion combined with the movement of the magma. The fine-grained groundmass represents the part of the solution which consolidated fairly rapidly and under diminished pressure when the molten mass was erupted as a lava flow or became emplaced as a minor intrusive body near the surface of the earth. The phenocrysts belong to the earlier or *intratelluric* stage, the groundmass to the final or *volcanic* stage in the story of the crystallisation of the rock.

When these stony aphanitic rocks are studied in thin slices under the microscope it becomes evident that the groundmass is variable in texture.

PLATE VIII



1. Spherulitic Obsidian. Natural size.



2. Banded Obsidian. Natural size.

[*To face page* 36

In many cases it is thoroughly crystalline and is then termed *microcrystalline*; in others the small crystals may be accompanied by larger or smaller amounts of cryptocrystalline material or of undifferentiated glass, in which case it is said to be *hemicrystalline* or *hypocrystalline*. The presence of perlitic structure in the cryptocrystalline or in the microcrystalline material may be regarded as evidence that many stony aphanitic rocks are devitrified glassy rocks. Microcrystalline and cryptocrystalline textures, indeed, may be the result either of direct crystallisation from solution or of the devitrification of glass—that is, they may be either primary or secondary in origin. Vesicular, spherulitic (see Plate VII. 3), and fluxion structures are just as characteristic of the lithoidal as of the vitreous aphanitic rocks.

Phanerocrystalline Rocks. *Their General Characters.*—The holocrystalline character of these rocks is evident even to the unaided eye. They show a wide range in the average diameter of the constituent minerals, which, in the fine-grained types, may be less than a millimetre, and in the normal coarse-grained types may be several centimetres. Exceptionally coarse-grained varieties, known as pegmatites, are distinguished also by great irregularity in texture. The medium- to coarse-grained rocks of the group, most of which have consolidated under more or less deep-seated conditions and are often classed as plutonic rocks, are typically granular and even-grained and only occasionally porphyritic. In some, as for example in granites, the minerals are dominantly hypidiomorphic and the structure is *hypidiomorphic granular* (granitoid) (see Plate XI. 2); in others, because of the long-continued growth of the majority of the constituents and their consequent mutual interference, nearly all the minerals are devoid of crystal boundaries and the texture is *xenomorphic granular*. The fine-grained rocks are often conspicuously porphyritic. *Orbicular* structure, in which there is a grouping of minerals either concentrically or radially to form *spheroids*, is met with in some granites and diorites (see Plate XIII. 1). In some cases the spheroids may have developed as a result of oscillatory crystallisation, in others it is clear that they have arisen through interaction between the magma and enclosed fragments of foreign rock (xenoliths). Fluxional arrangements of the constituents is rare in the fine-grained phanerocrystalline rocks, but is not uncommon in the coarser varieties where these have been subjected to lateral pressure during the crystallisation period, as, for example, in some gneissoid granites. Vesicular structure is absent, but irregularly bounded cavities, usually lined with well-terminated crystals and known as *miarolitic* or *drusy* cavities, are sometimes abundant, as in the granites of the Mourne Mountains (see Plate IX. 2).

MINERAL INGREDIENTS OF IGNEOUS ROCKS

Primary Minerals.—Those constituents which crystallised directly from a magma are termed *primary* to distinguish them from minerals of later origin which are *secondary*. Two kinds of primary minerals are recognised —namely, (*a*) **Essential** and (*b*) **Accessory** minerals. Essential minerals are those whose presence is implied in the definition of a rock. They are normally those which are present in considerable quantity. Accessory minerals, on the other hand, may or may not be present in any particular sample of the rock: some, the *common* accessory ingredients, are usually present; others, the *minor* accessory constituents, occur only sporadically.

Secondary Minerals.—During the waning period of the cooling and consolidation of igneous rocks active gases and vapours are evolved from residual fluids, and often bring about extensive mineralogical transformations in the primary minerals of those rocks and also in the minerals of surrounding rocks; changes brought about in this way are said to belong to the *pneumatolytic stage*. Later, at the *hydrothermal stage*, other mineral changes are induced by the passage of hot solutions. And, finally, extensive chemical and mineralogical alterations are produced by the ordinary low-temperature "weathering" of rocks. The new minerals which result from such activities are grouped as secondary. The secondary minerals not only replace in whole or in part the primary or original constituents, but they are frequently met with lining or filling cracks and fissures or occupying the vesicular and miarolitic cavities in igneous rocks.

The more important primary and secondary minerals may be tabulated as follows:—

PRIMARY OR ORIGINAL MINERALS

In list I. we include the most important, namely, those which have the widest distribution and occur most abundantly—those, in short, which are the chief ingredients of the commonest igneous rocks. All the minerals in the list are essential constituents in some rocks, and accessory ingredients in others:—

I.

1. Quartz.
2. Feldspars.
3. Pyroxenes.
4. Amphiboles.
5. Micas.
6. Olivine.
7. Nepheline.
8. Leucite.

The minerals named in list II. are of less importance—the igneous rocks of which they are essential constituents being of more local occurrence. As accessory ingredients, however, they play a notable part:—

II.

1. Sodalite.
2. Haüyne.
3. Nosean.
4. Analcite.
5. Garnet.
6. Tourmaline.

The minerals in list III. occur chiefly as accessory ingredients, and are thus of subordinate importance to those already mentioned, but they are all very widely distributed:—

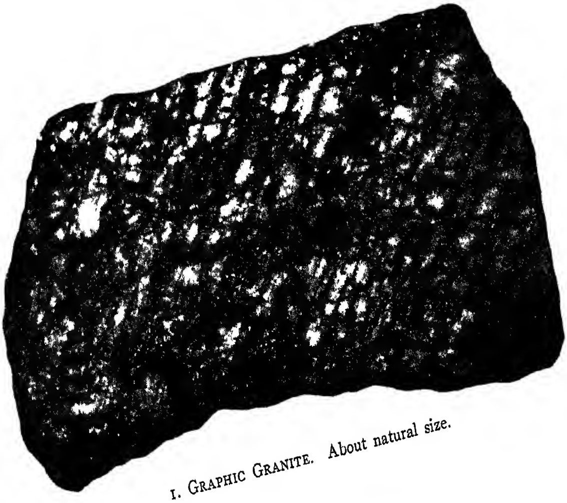
III.

1. Apatite.
2. Magnetite.
3. Ilmenite.
4. Hæmatite.
5. Pyrite.
6. Zircon.
7. Rutile.
8. Sphene.

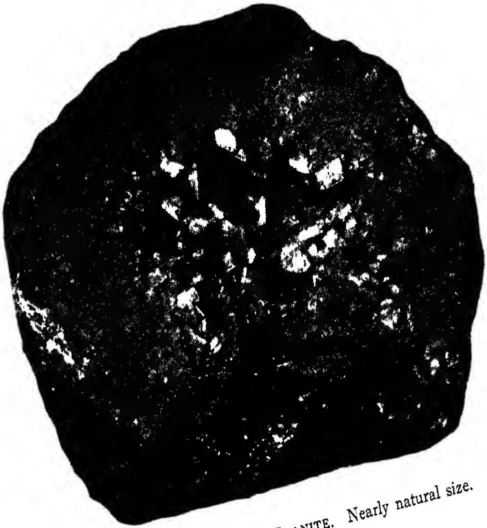
List IV. includes accessory ingredients which are not so widely distributed as those already mentioned:—

IV.

1. Spinel.
2. Chromite.
3. Picotite.
4. Pyrrhotite.



1. Graphic Granite. About natural size.



2. Druse or Geode in Granite. Nearly natural size.

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Secondary Minerals

There are many minerals of secondary origin, but only the more commonly occurring ones are mentioned in the following list :—

1. Quartz, opal, chalcedony.
2. Iron oxides.
3. Calcite and other carbonates.
4. Kaolin.
5. Micas.
6. Chlorite.
7. Uralite.
8. Serpentine.
9. Talc.
10. Epidotes.
11. Leucoxene.
12. Zeolites.
13. Albite.
14. Fluorspar.

Classification of Crystalline Igneous Rocks

Modern classifications of these rocks are of three kinds : (*a*) classifications based on mineral composition and texture ; (*b*) classifications based on chemical composition ; and (*c*) classifications in which mineral composition, chemical characters, and textural variations are all taken into account. Some classifications are qualitative ; others are in part quantitative, and a few, both chemical and mineralogical, are thoroughly quantitative. In many of the mineralogical classifications mode of occurrence in the field is used also as a factor—sometimes as the first factor—as when the rocks are grouped as (a) *Plutonic*, (b) *Hypabyssal*, (c) *Effusive*. In others, and even in those in which in other respects chemical factors are ignored, silica percentage is given a leading place, and crystalline igneous rocks are classified into (a) *Acid*, with silica above 66 per cent., (b) *Intermediate*, with silica between 66 and 55 per cent., and (c) *Basic*, with silica below 55 per cent. Some recent mineralogical classifications emphasise the principle of silica saturation—" saturated " is a term applied to minerals which are capable of forming in the presence of free silica—and three groups of crystalline igneous rocks are recognised : (a) *Oversaturated*, characterised by quartz ; (b) *Saturated* ; and (c) *Undersaturated*, comprising three sub-groups characterised respectively by olivine, by feldspathoids, and by olivine and feldspathoids. Even when not used as the primary basis of classification the principle of saturation is frequently made use of in making minor mineralogical sub-divisions.

For a student who desires only an elementary knowledge of the crystalline igneous rocks the two factors which make the most direct appeal are mineralogical composition and texture. The limited number of essential minerals in common igneous rocks and the ease with which they can be determined, the importance of the distribution of the feldspathic silicates, and the textural variations in rocks with the same mineral content can be readily appreciated. In the classification adopted here the common types to be studied are arranged in the following mineralogical groups :—

I. *Feldspathic Rocks with Abundant Quartz.*
  (*a*) The Granite-Rhyolite Series.
  (*b*) The Granodiorite-Rhyodacite Series.
  (*c*) The Quartz Diorite-Dacite Series.

II. *Feldspathic Rocks, free from or poor in Quartz or Feldspathoids.*
  (*a*) The Syenite-Trachyte Series.
  (*b*) The Diorite-Andesite Series.
  (*c*) The Gabbro-Basalt Series.

III. *Feldspathic Rocks with Abundant Feldspathoids.*
  (*a*) The Nepheline Syenite-Phonolite Series.
  (*b*) The Theralite-Basanite Series.

IV. *Feldspathoidal Rocks, free from or poor in Feldspars.*

V. *Rocks with neither Feldspars nor Feldspathoids essential.*

I. FELDSPATHIC ROCKS WITH ABUNDANT QUARTZ

This group includes the granites, granodiorites and quartz diorites and their fine-grained equivalents. They are all oversaturated rocks containing more than 10 per cent. of quartz. In the granites alkali feldspars (orthoclase, perthite, and microcline) may be the only feldspars present and always occur in greater abundance than soda-lime feldspars. In the quartz-diorites the feldspar may be exclusively soda-lime feldspar and orthoclase is never present in large amount. Granodiorites occupy an intermediate position; soda-lime feldspars are dominant but are accompanied by noteworthy amounts of orthoclase.

(a) The Granite-Rhyolite Series

Regarded from the point of view of textural variation, this series includes *Granites*, *Microgranites*, and *Rhyolites*. The upper textural limit for micrograntes is reached when the maximum diameter of the majority of the roughly equidimensional grains of quartz and feldspar, phenocrysts being ignored, is 0·5 mm.; the corresponding upper grain limit for rhyolites is 0·05 mm. When the feldspars are lath-shaped it is convenient, for rapid determination, to use the length of the majority of these, which should not exceed 1 mm. for microgranites and 0·12 mm. for rhyolites.

Granites are phanerocrystalline aggregates of quartz, alkali feldspars (usually accompanied by larger or smaller amounts of acid plagioclases), and a ferromagnesian silicate mineral or minerals which may be used to distinguish varieties of granite. The most common ferromagnesian silicate is biotite which is often associated with muscovite; hornblende is of not infrequent occurrence, alone or together with biotite; soda-amphiboles, such as arfvedsonite, and soda-pyroxenes, such as ægirine and ægirine-augite, are found in granites derived from soda-rich magmas; hypersthene is the chief ferromagnesian silicate in the somewhat rare alkali-rich granite known as *charnockite*. Common accessory minerals are zircon, apatite, magnetite, and sphene. The colour of the rocks, which depends largely on that of the feldspars, is usually light or dark grey, pink or reddish; occasionally it is greenish.

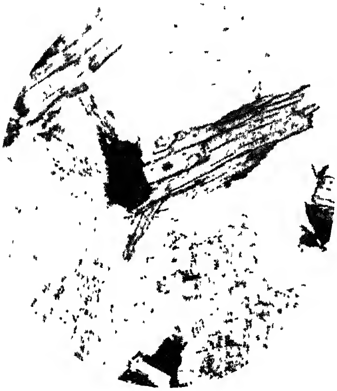
Granites show a wide range in the degree of coarseness of their crystallisation. Although typically even-grained, hypidiomorphic granular (granitoid) in texture, they are occasionally porphyritic, phenocrysts of orthoclase sometimes attaining a length of as much as seven inches. In some, termed *graphic granites* (see Plate IX. 1), in which potash feldspars and quartz are the only essential constituents, these two minerals have crystallised simultaneously and are intergrown in such a manner that adjacent patches of each mineral are in optic continuity. Such intergrowths have been called "graphic" because of their supposed resemblance to Hebrew writing; they are sometimes termed "granophyric." *Spheroidal* or *Orbicular* structures are occasionally found, as in some of the granites of Finland. When granites have crystallised while subjected to lateral pressure they may show a rudely parallel arrangement of their constituents giving a primary gneissoid banding. Miarolitic or drusy cavities are often met with, as in the granites of the Mourne Mountains (see Plate IX. 2), the druses being lined with euhedrally-terminated crystals of smoky quartz, feldspars, topaz, etc. Many granites exhibit, sometimes in abundance, light-coloured and dark-coloured patches obviously different from the general mass of the rock. These have been found to be in some cases segregations of late-formed or early-formed constituents respectively; in other cases they are xenolithic in character, either *cognate xenoliths*, of magmatic origin but older than the enclosing rock, or *accidental xenoliths*, fragments of other rocks caught up by the granite magma.

Varieties of granite have been named in several ways. Those in which alkali feldspars are present to the exclusion or almost complete exclusion of soda-lime feldspars are known as *alkali-granites*, those with noteworthy amounts of soda-lime feldspars as *calc-alkali-granites*. Or they may be distinguished by prefixing the names of the other essential minerals which accompany the quartz and feldspars as, for example, *muscovite-biotite-granite* (see Plate X. 1), *biotite-granite*, *hornblende-granite*, *arfvedsonite-granite*, etc. A variety in which ferromagnesian silicates are in negligible amount has been called *aplogranite*. Granites modified by pneumatolitic agents include the following:—*greisen*, consisting essentially of quartz and muscovite and often carrying topaz, cassiterite, etc.; *schorl rock*, made up mainly of quartz and tourmaline, all or nearly all the feldspar and biotite having been replaced, and *luxulyanite*, another tourmaline-rich type in which much of the feldspar remains more or less unmodified (see Plate X. 2); and *china-clay rock*, an aggregate of hydrated silicates of alumina, muscovite, and quartz, with sometimes tourmaline. Textural and structural characters have been utilised in distinguishing *orbicular granite*, *graphic granite*, *granite-gneiss*, and *pegmatite* or *giant granite*.

Microgranites.—These rocks are similar to granites in composition but are finer-grained in texture. The maximum diameter of the majority of the quartz and feldspar grains in the groundmass lies between 0·5 and 0·05 mm. The rocks are typically light in colour, usually some shade of red or grey, since quartz and feldspars are the dominant constituents. The accompanying micas, amphiboles, and pyroxenes occur in relatively small amount. They are often conspicuously porphyritic, the chief phenocrysts being quartz, orthoclase, and oligoclase. Not infrequently the quartz has the form of corroded bipyramidal crystals. Sometimes phenocrysts consisting of graphic intergrowths of quartz and orthoclase can be noted. The commonest ferromagnesian phenocryst is biotite. As seen in hand specimens the groundmass ranges from finely phanerocrystalline to compact types in which the majority of the grains have reached the limit of unaided vision. Microscopic examination shows that in many cases much of

PLATE X

MICROSCOPIC STRUCTURE OF MINERALS AND ROCKS



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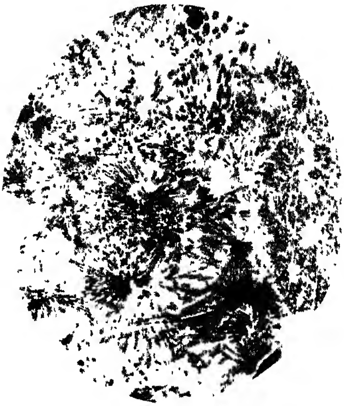

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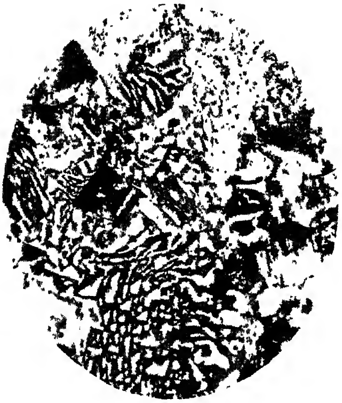

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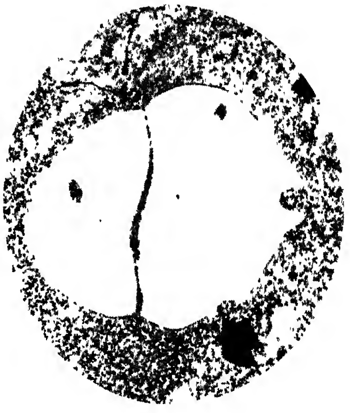

4.

1. Muscovite-biotite-granite, Ardclach, Nairn. Shows quartz, feldspars (orthoclase and oligoclase), biotite (with included zircon and apatite) and muscovite. Texture granitoid. × 20
2. Luxulyanite, Cornwall. Quartz with needles of tourmaline; turbid orthoclase on right. × 35.
3. Graphic micrograntite (granophyre), Rosskopf, near Barr, Vosges Mts., showing micrographic intergrowth of quartz and orthoclase. Nicols crossed. × 35.
4. Quartz-porphyry, Clochnahill, Kincardineshire. Phenocrysts of orthoclase (top), corroded quartz (centre) and small biotites (black) in microcrystalline groundmass of quartz, orthoclase and secondary iron oxides. × 20.

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the quartz and orthoclase of the groundmass occurs in micrographic intergrowths.

The microgranites are widely distributed as hypabyssal intrusions and as apophyses of granite masses. Many of the rocks which have been called *quartz-porphyry* belong to this group (see Plate XI. 1 and Plate X. 4), but others, because of the finer grain of their groundmass are varieties of rhyolite. Microgranites with a dominating development of micrographic quartz-orthoclase intergrowths have been termed *granophyres* (see Plate X. 3). Here, too, may be placed *aplites* which consist mainly of a fine-grained saccharoidal (xenomorphic) aggregate of quartz and alkali feldspars. In these the ferromagnesian silicates are absent or in very small amount, but muscovite is often present and topaz, tourmaline, and garnet are common accessories. The aplites, which represent the consolidation of residual mother-liquor, are found in thin veins traversing the parent granite masses but occasionally penetrate the surrounding rocks; sometimes, indeed, they form independent intrusions of considerable size.

Rhyolites.—The rocks in this group include all the aphanitic members of the series. They may be stony or glassy, or glassy and stony bands may alternate in the same specimen. The name rhyolite was given originally because of the frequent occurrence of fluidal or flow structures which are often conspicuous alike in the stony and the glassy types. In the former the maximum diameter of the majority of the feldspar and quartz grains of the groundmass is less than 0·05 mm. Because of their occurrence in the Lipari Islands these rocks have also been called *liparites*. The rhyolites may be porphyritic or non-porphyritic. The most usual phenocrysts are corroded crystals of quartz, and these may be accompanied by phenocrysts of glassy sanidine, acid plagioclase, biotite and, less often, amphiboles and pyroxenes. The groundmass may be microcrystalline, cryptocrystalline, or vitreous, but very commonly it consists of alternating laminæ and streaks of these materials. Such alternations give evidence of fluxion, but this is evident also even in apparently homogeneous glassy types which usually show more or less parallel alignment of their microlites when examined under the microscope. Spherulitic and perlitic structures are characteristic of the vitreous and cryptocrystalline phases. The rocks often exhibit finely porous or cellular structure, and, not infrequently, spherical, flattened, and irregularly-shaped cavities appear, which may be lined with tridymite, quartz, opal, chalcedony, etc. Most of the rocks which have been called *felsite* are rhyolites with cryptocrystalline groundmass.

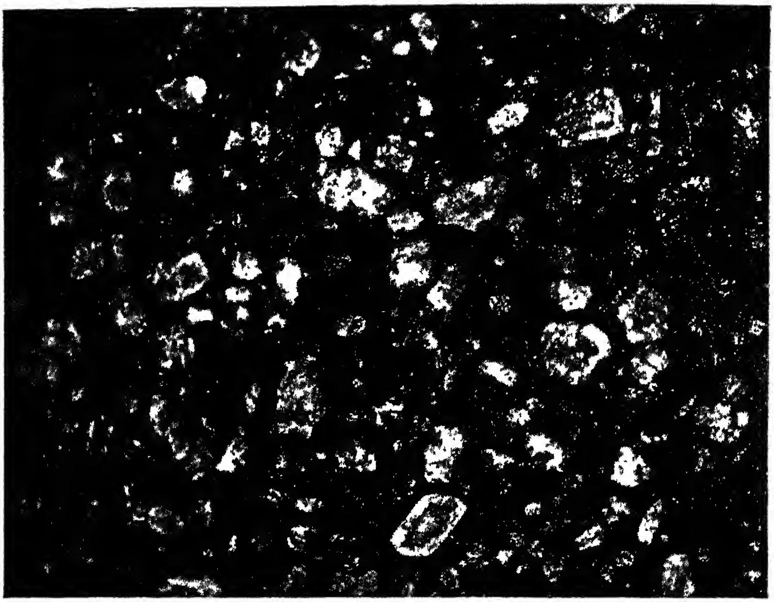
The vitreous rhyolites are known as *Rhyolitic Pitchstone* and *Rhyolitic Obsidian.* **Pitchstone** is usually dark green or black in colour, but lighter green, red, brown, and yellow varieties are also found. The lustre of the rock is typically pitch-like or resinous; the fracture may be conchoidal, but is often irregular or splintery. Under the microscope pitchstones are seen to be crowded with crystallites and microlites, the latter sometimes arranged in beautiful plumose and stellate groups (see Plate VII. 1). Skeletal crystals, too, are common. Phenocrysts now and again abound: they are commonly either quartz or glassy feldspars; pyroxenes, both monoclinic and orthorhombic, hornblende, and biotite all occur, and occasionally, as in some of the Arran pitchstones, fayalite, an iron olivine, also appears. Chemically, pitchstones are distinguished from obsidians by their higher content of water. **Obsidian** is typically black in colour, but may be dark grey, or rarely red or brown. The lustre is vitreous and the fracture conchoidal. Phenocrysts are rare. Spherulitic, vesicular, and perlitic structures are common. Sometimes crystallites and microlites are abundantly developed; in other cases the rock is almost devoid of such bodies.

Pitchstones occur occasionally as lava flows. They are more widely distributed, however, as dykes and sills, as in the case of the well-known pitchstones of the island of Arran. Among localities for typical obsidians may be mentioned the Lipari Islands, Hungary, and Obsidian Cliff in the Yellowstone National Park. Lithoidal rhyolites are of frequent occurrence, particularly among the older Palæozoic suites of lavas in many parts of the world. Characteristic examples with good fluxion structures may be studied, for instance, among the lavas of Lower Old Red Sandstone age in Glen Coe. They are common also as minor intrusive bodies.

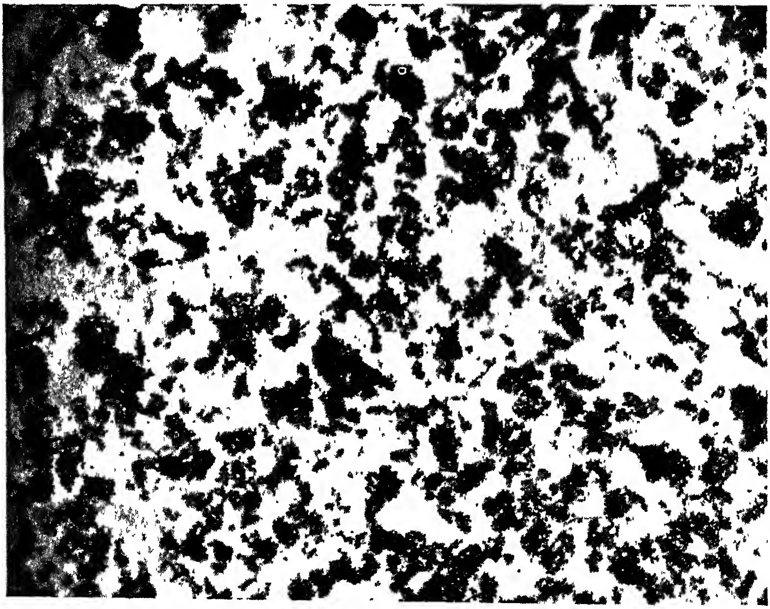
(b) The Granodiorite-Rhyodacite Series

Here are included *granodiorites*, *microgranodiorites* and *rhyodacites*, which correspond respectively in grain size to the granites, microgranites, and rhyolites of the preceding series.

Granodiorites are intermediate in composition between calc-alkali-granites and quartz-diorites. Acid plagioclases are



1. PORPHYRITIC STRUCTURE. QUARTZ-PORPHYRY. Natural size.



2. GRANITOID STRUCTURE. TONALITE. Natural size.

[To face page 45

in excess of the potash feldspars, but the latter are always present to the amount of at least 5 per cent. of the total feldspar. The potash feldspars, as in the granites, may be orthoclase, microcline, or one of the perthitic feldspars ; the plagioclase is chiefly oligoclase or andesine. Biotite and hornblende are the commonest ferromagnesian silicates, but augite and hypersthene occur occasionally. The usual accessory constituents are sphene, apatite, and magnetite. The granodiorites have hypidiomorphic, granular (granitoid) texture. Some of the so-called " orbicular granites " of Finland are granodiorites. Like the granites the granodiorites are of widespread occurrence as major plutonic intrusions. Daly has given the area of the granodiorite mass of the Sierra Nevada as approximately 20,000 square miles.

Microgranodiorites.—This term includes all medium-grained rocks with the composition of granodiorites. They are often strongly porphyritic. They occur as apophyses of granodiorite intrusions and as independent dykes and sills.

Rhyodacites are the fine-grained aphanitic equivalents of the granodiorites. They are usually porphyritic, the phenocrysts including quartz, acid plagioclase, biotite, hornblende, and augite. The groundmass, which often shows good fluxion structures, may be microcrystalline, cryptocrystalline, or glassy. Rhyodacites cannot be distinguished from dacites in hand specimens, and, when the groundmass is wholly or in part cryptocrystalline or glassy, they can be distinguished from rhyolites and dacites only with the aid of chemical analyses.

(c) The Quartz-Diorite-Dacite Series

To this series belong quartz-feldspar rocks in which all the essential feldspar is plagioclase. Orthoclase may be present in small amount but is regarded as accessory. The coarse-grained types are known as *quartz-diorites*, the medium-grained as *quartz-microdiorites* and the fine-grained as *dacites*. The textural limits are the same as in (*a*) and (*b*).

Quartz-diorites.—These are rocks with granitoid texture, and, apart from their poverty in orthoclase, closely resemble granodiorites. Some of the orbicular " diorites " belong to this type. The name *tonalite*, given originally to a rock which is a hornblende-biotite-quartz-diorite (see Plate XI. 2), is used by some writers as the group name. A quartz-rich variety of tonalite with ferromagnesian silicates in very small amount has been designated *trondhjemite*.

Quartz-microdiorites.—Here are included rocks intermediate in texture between quartz-diorites and dacites. They are for the most part porphyritic. Many of the hypabyssal rocks formerly called *quartz-porphyrites* are porphyritic quartz-microdiorites.

Dacites are the fine-grained aphanitic equivalents of quartz-diorites. When fresh they are usually some shade of grey or pale brown, but when altered they may be darker brown or reddish in colour. They are generally porphyritic, and may show phenocrysts of quartz and acid plagioclase along with biotite, hornblende, or pyroxenes. The groundmass may be microcrystalline, cryptocrystalline, or glassy. Vesicular, fluxion, spherulitic and perlitic structures are common. The highly vitreous types, *dacitic obsidian* and *dacitic pitchstone*, can be distinguished from rhyolitic glassy rocks only by chemical analyses.

II. FELDSPATHIC ROCKS FREE FROM OR POOR IN QUARTZ OR FELDSPATHOIDS

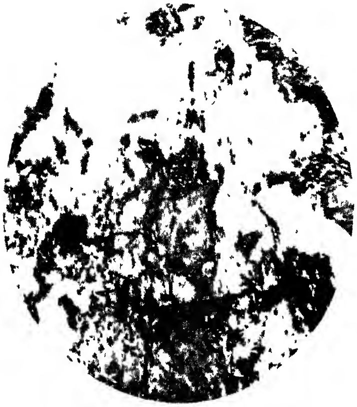
(a) The Syenite-Trachyte Series

The coarse-, medium-, and fine-grained rocks in this series may be grouped as *syenites*, *microsyenites*, and *trachytes*. Trachytes are typically much coarser than rhyolites; the upper limit for the length of the majority of the lath-shaped feldspars of the groundmass may be taken as 0·5 mm., while the corresponding limit for microsyenites is the same as for microgranites, namely 1 mm.

Syenites are coarsely crystalline rocks with granitoid texture and consist of alkali feldspars accompanied by larger or smaller amounts of acid plagioclases, together with ferromagnesian silicate minerals (Plate XII. 1). They are distinguished from granites by the complete or almost complete absence of quartz. In some varieties the alkali feldspar is chiefly orthoclase, in others microperthite. Albite and anorthoclase are also found. Hornblende, biotite, and augite are the common ferromagnesian silicates in types with large amounts of oligoclase, while soda-amphiboles and soda-pyroxenes are characteristic of the alkaline, soda-rich rocks. Since the syenites are rarely exactly saturated rocks it is usual to find the feldspar accompanied by small amounts either of quartz

PLATE XII

Microscopic Structure of Minerals and Rocks



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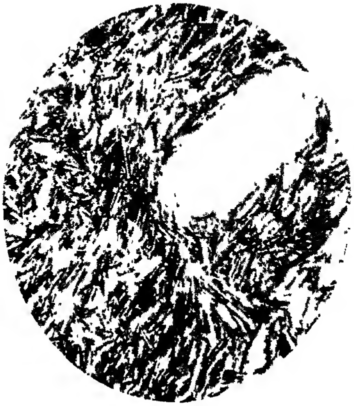

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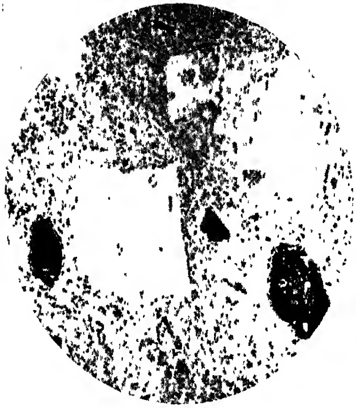

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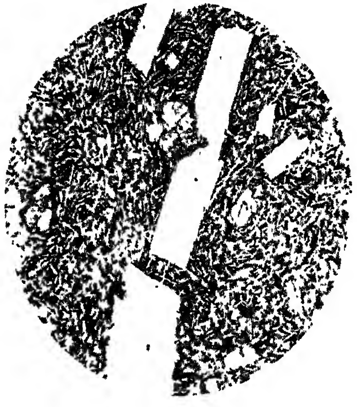

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1. Syenite (Nordmarkite), Tonsenås, Oslo. Chiefly microperthite; biotite near centre; small accessory crystals of magnetite. Texture granitoid. Nicols crossed. ×20.
2. Quartz-trachyte, Craig's Quarry, Dirleton, showing phenocrysts of sanidine in a trachytic groundmass which consists mainly of laths of sanidine together with interstitial quartz, augite and iron oxides. Nicols crossed. ×20.
3. Hornblende-andesite, Bogincabers, Kincardineshire, showing phenocrysts of "resorbed" hornblende (black), plagioclase and hypersthene (replaced by bastite and calcite) in a pilotaxitic groundmass. ×20.
4. Hypersthene-andesite, Knock Hill, Kincardineshire, Phenocrysts of hypersthene and plagioclase in a hyalopilitic groundmass consisting of microlites of plagioclase, granules of augite and minute magnetites set in abundant glassy base. ×20.

or of the common feldspathoids, such as nepheline or sodalite. Other accessory minerals are sphene, apatite, zircon, magnetite, and ilmenite.

As in the case of granites two main groups of syenites have been recognised—*alkali syenites* and *calc-alkali syenites*; the latter contain large amounts of soda-lime feldspars. The alkali syenites, which occur more frequently than the others, have sometimes been classified by prefixing the name of the dominant soda-rich amphiboles or pyroxenes, e.g. *riebeckite-syenite*, *ægirine-syenite*, etc.; or, they have been given special names such as *nordmarkite*, *pulaskite*, *larvikite*, *perthosite*, etc. Nordmarkite, named after the district of Nordmark, near Oslo, has as its chief constituent microperthite; quartz is rather abundant and the ferro-magnesian silicates, which are in very small amount, include biotite and arfvedsonite. Similar rocks have been described from localities in the northern and north-western Highlands of Scotland. Pulaskite, a name first given to a somewhat similar rock from Pulaski County, Arkansas, differs from nordmarkite in sometimes carrying small amounts of nepheline or sodalite; a variety of pulaskite containing a little ægirine-augite is abundantly developed in the Ben Loyal complex in Sutherland. Larvikites, which are the predominating rocks in the coastal region between Tönsberg and Langesundsfjord in Southern Norway, are readily recognised by the rhombic cross-sections of the feldspars which are soda-orthoclase and anorthoclase. Nepheline and olivine, a rare mineral in syenites, are usually present in these rocks. *Perthosite*, described by Dr J. Phemister, is a soda-syenite with 97 to 98 per cent. of perthitic feldspars occurring in the Loch Ailsh district of Sutherlandshire.

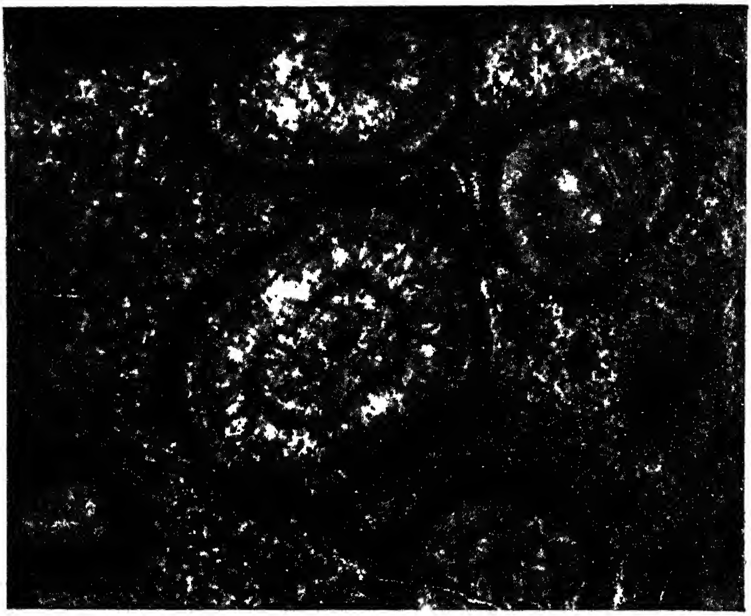
The calc-alkali syenites include *hornblende-syenites*, *biotite-syenites*, and *augite-syenites*. Here may be mentioned also the *monzonites*, which have approximately equal amounts of orthoclase and plagioclase, and occupy a position between syenites and diorites, and the somewhat more basic *olivine-monzonites*. Good examples of the latter have been described from Kentallen and elsewhere in the western Scottish Highlands, and one variety has been named *kentallenite*.

Microsyenites.—Included here are medium-grained rocks which are the mineralogical equivalents of the syenites and trachytes, together with others which, while having similar grain, are regarded as acid (aplitic) and basic (lamprophyric) differentiates. Some are non-porphyritic, others conspicuously porphyritic.

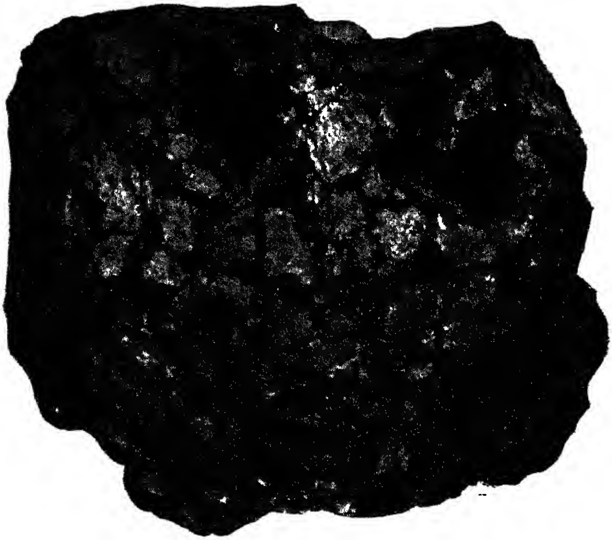
The rocks termed *syenite-porphyry* are porphyritic microsyenites. The name *orthoclase-porphyry* was formerly applied to most hypabyssal rocks of syenitic composition with conspicuous orthoclase phenocrysts irrespective of the textural character of the groundmass; it includes both microsyenites and trachytes in the sense in which it is now proposed to use these terms. *Rhomb-porphyries* also, which are the finer-grained hypabyssal and effusive equivalents of larvikite, include both microsyenitic and trachytic varieties if the rocks are classified on the basis of groundmass texture. *Bostonites*, which consist almost entirely of alkali feldspars, are acid differentiates. They are characterised by a roughly parallel arrangement of their tabular feldspars. *Minettes* ("syenitic mica-traps") and *vogesites* are basic or lamprophyric differentiates. In both types the feldspar is chiefly orthoclase, but the dominant ferromagnesian silicate in the minettes is biotite, while in the vogesites it may be either hornblende or augite. The minettes are typically porphyritic with very numerous phenocrysts of biotite, the groundmass consisting mainly of biotite and orthoclase. Hornblende, augite, and olivine sometimes occur as accessory minerals, and quartz may be present in the groundmass either interstitially or in micrographic intergrowth with feldspar. Other common accessory minerals are apatite and iron ores. Less frequently the minettes are even-grained, non-porphyritic rocks. Like the minettes the vogesites are dark-coloured, grey to black rocks which may be either porphyritic or even-grained. The phenocrysts are chiefly hornblende and augite, and these minerals appear again along with orthoclase in the groundmass. Common accessory minerals are plagioclase, biotite, olivine, apatite, and iron oxides. The minettes and vogesites, like other lamprophyres, weather very readily and are usually richly charged with secondary products such as calcite and chlorite. Although grouped here with the medium-textured syenitic rocks some of the minettes and many of the vogesites are finely aphanitic.

Trachytes.—The name "trachyte," now applied to all the fine-grained equivalents of the syenites, was given originally by Haüy to rocks from the Drachenfels on the Rhine because of their rough appearance. Trachytes are in general light in colour in hand specimens—usually white, grey, yellowish, or pink—but, when altered, they often become reddish-brown. They are characterised by a noteworthy development of phenocrysts of sanidine, sometimes accompanied by others of acid plagioclase. Less conspicuous and less abundant are small phenocrysts of biotite, amphiboles, and pyroxenes. The groundmass is normally aphanitic and stony, very rarely glassy; it is often highly porous. Under the microscope the groundmass of trachytes is seen to be, as a rule, holocrystalline and to consist dominantly of small laths and microlites of sanidine with a pronounced flow-arrangement, giving the texture known as trachytic (see Plate XII. 2). Between the sanidine laths in the calc-alkali trachytes occur in small amount granules of augite, and in the commoner soda-trachytes the sanidine is accompanied by soda-rich ferromagnesians such as ægirine, ægirine-augite, and arfvedsonite, the last occurring in characteristic "mossy" growths. A common feature is the presence in the groundmass of either a little interstitial quartz or small amounts of nepheline, analcite, or sodalite. Iron oxides, sphene, zircon, and apatite are common accessories.

PLATE XIII



1. ORBICULAR GABBRO (CORSITE, NAPOLEONITE). Nearly natural size.



2 VOLCANIC TUFF. Two-thirds natural size.

[*To face page* 49

The commonest trachytes are *alkali-trachytes*, and in particular soda-trachytes; *calc-alkali-trachytes* are found much less frequently. Varieties have been named from mineralogical peculiarities—sometimes by prefixing the name of the dominant ferromagnesian constituent, e.g. *biotite-trachyte*, *ægirine-trachyte*, *arfvedsonite-trachyte*, etc., sometimes by indicating the occurrence in small amount of quartz or feldspathoids as in *quartz-trachyte*, *sodalite-trachyte*, etc. The nepheline-bearing trachytes have also been distinguished by the term *phonolitic trachyte*. *Keratophyres* are trachytes in which the feldspar is mainly a soda-rich variety, albite or albite-oligoclase. *Trachy-andesite* and *trachy-basalt* are names given to the fine-grained equivalents of the monzonites and olivine-monzonites respectively.

Trachytes are of common occurrence among the effusive products of Tertiary and Recent volcanoes, and they are no less abundant in the suites of lavas from the older Palæozoic centres of eruption. They occur also as minor intrusive bodies. In this country, for example, potash-trachytes of Old Red Sandstone age are met with in the Pentland Hills and the Braid Hills in the Edinburgh district, keratophyres are found among the Ordovician and Devonian lavas of England, and trachytes, both effusive and intrusive, of Carboniferous age, occur in the Garleton Hills, in the Eildon Hills and elsewhere in south-eastern Scotland.

(b) The Diorite-Andesite Series

This series comprises crystalline igneous rocks in which the essential feldspar consists entirely of acid plagioclase, ranging from oligoclase to andesine. It includes the coarse-grained *diorites*, the medium-grained *microdiorites*, and the fine-grained *andesites*. The upper limit for the length of the majority of the feldspar laths of the groundmass of andesites may be taken as 0·25 mm.; the corresponding limit for microdiorites is 1 mm.—the same as for microgranites and microsyenites.

Diorites are rocks of granitoid texture consisting of acid plagioclases together with one or more of the common ferromagnesian silicates, hornblende, biotite, augite, and hypersthene. They are not often porphyritic. Sometimes they exhibit primary gneissic banding and orbicular structures are of occasional occurrence. The average diorite is finer in grain than most granites. The common varieties are rather rich in ferromagnesian constituents and are darker in colour than granites and syenites. Quartz is present in small amount in most diorites and accessory orthoclase is also found. Other accessory minerals include apatite, zircon, sphene, and iron oxides.

Diorites are classified according to the nature of the chief ferromagnesian silicates as *hornblende-diorite*, *biotite-diorite*, *biotite-hornblende-diorite*, *augite-diorite* and *hypersthene-diorite*. The well-known orbicular " diorite " of Corsica, sometimes designated *corsite* or *napoleonite* (Plate XIII. 1), should be grouped with the gabbros since the average feldspar of the rock is labradorite.

Diorites do not have a wide distribution. They seldom occur as independent intrusions of any considerable size, but are met with not infrequently as apophyses and marginal modifications of granite and granodiorite masses.

Microdiorites.—These rocks are mineralogically the equivalents of the diorites, but they are finer in texture and are for the most part strongly porphyritic. They occur as hypabyssal intrusions.

Included here are many of the *porphyrites* (diorite-porphyrites), a term which, until recently, was used by most workers in this country for all porphyritic hypabyssal intrusions of dioritic composition. If igneous rocks are classified according to texture, however, many of the so-called " porphyrites " are indistinguishable from andesites. By earlier workers in this country " porphyrite " was applied to weathered andesites, and it is used by German geologists for andesites of pre-Tertiary age. Two lamprophyric varieties may be mentioned—*kersantite* (" dioritic mica-trap "), which consists essentially of a xenomorphic to hypidiomorphic granular aggregate of andesine and biotite, with phenocrysts of biotite and hornblende, and *spessartite*, a type in which abundant phenocrysts of hornblende and sporadic phenocrysts of plagioclase are set in a holocrystalline groundmass consisting mainly of acid plagioclase and needles of hornblende.

Andesites, the fine-grained aphanitic equivalents of the diorites, have a wide distribution as lava-flows and occur also as minor intrusions. They are in general porphyritic and range in colour from light grey through shades of brown, red, and green to black. The phenocrysts include plagioclases and the common ferromagnesian silicates, biotite, hornblende, augite, and hypersthene. Under the microscope the feldspar phenocrysts are seen to be zoned—a core of basic andesine or acid labradorite being succeeded by zones usually progressively richer in soda; the hornblendes and biotites in general show more or less evidence of " resorption " and are replaced marginally or completely by black granular aggregates of magnetite and augite (see Plate XII. 3). The groundmass is variable in texture, all gradations being found from microcrystalline to completely glassy. Most commonly, perhaps, it is microcrystalline or almost so, and the typical andesitic groundmass consists of a finely-felted aggregate of minute laths and microlites of oligoclase in the interstices of which occur crystals and microlites of augite, granules of iron oxide, and small amounts of badly differentiated feldspathic material and occasionally a little glass. This type of texture is termed *pilotaxitic* (Plate XII. 3). Very often, however, the texture is *hyalopilitic*, a term applied when the feldspars, augites, and iron oxides of the groundmass are set in abundant glass (Plate XII. 4). Completely glassy types are also found. The usual accessory minerals are sphene, apatite, magnetite, orthoclase, and pyrites.

Andesites are named from the character of the dominating ferromagnesian minerals. Common varieties are *biotite-andesite*, *hornblende-andesite*, *augite-andesite*, and *hypersthene-andesite*. Completely or nearly completely glassy types are known as *andesitic pitchstone*. The term *propylite* has been used for andesites which, having been subjected to intense hydrothermal activity, have undergone marked and varied changes in mineralogical composition and texture.

Andesites bulk largely among the lavas of Tertiary and later volcanic districts in many parts of the world; they are of widespread distribution also as lavas and dykes in older geological formations. In Britain, for example, they occur in the Cheviot Hills, the Pentland Hills, the Sidlaw Hills, the Ochils, and the Ben Nevis and Glen Coe regions in association with other volcanic rocks of Lower Old Red Sandstone age.

(c) The Gabbro-Basalt Series

Here again we are dealing with igneous rocks in which the dominating feldspars are plagioclases, but in this case they are basic or lime-rich, ranging from labradorite to anorthite. The coarse-grained representatives are known as *gabbros*, the medium-grained as *dolerites*, and the fine-grained as *basalts*. The maximum area for the majority of the plagioclase laths, porphyritic crystals being disregarded, is 1 sq. mm. for dolerite and 0·05 sq. mm. for basalt. For rapid determination in thin slices it is convenient to use the maximum *lengths* of the majority of the feldspar laths which is 2 mm. for dolerites and 0·5 mm. for basalts.

Gabbros are coarsely crystalline rocks, usually dark grey, dark green, or nearly black in colour. They are sometimes hypidiomorphic granular (granitoid), in other cases xenomorphic granular in texture. Basic plagioclases are essential constituents in all gabbros; the essential ferromagnesian silicates of common occurrence are pyroxenes, both monoclinic and orthorhombic, and olivine. The pyroxenes are often schillerised and exhibit pearly or sub-metallic lustre. Quartz is sometimes present in small amount. Primary amphiboles and micas are only rarely essential. Common accessory minerals include magnetite, ilmenite, pyrrhotite, chrome-spinels, and apatite. The gabbros have been sub-divided into varieties based partly on the character of the plagioclase, partly on that of the ferromagnesian silicates. In *normal gabbros* the essential minerals are basic plagioclase (chiefly labradorite) and a monoclinic pyroxene which may be augite, diallage, or diopside. Slightly oversaturated types in which quartz occurs, either interstitially or in graphic growth with orthoclase, have been called *quartz-gabbros*. Undersaturated varieties include *olivine-gabbro*, in which olivine is added to the constituents of normal gabbro (Plate XIV. 1), and *troctolite* (" troutstone ") which consists essentially of labradorite and olivine (Plate XIV. 2). When hypersthene in noteworthy amount accompanies the monoclinic pyroxene the rocks are called *hypersthene-gabbro*. Rocks in which hypersthene is the dominant pyroxene are known as *norites*, or, if olivine is also present, as *olivine-norites*. Varietal names have been given also to types characterised by containing more basic plagioclases (bytownite to anorthite). When these feldspars are accompanied by augite the rock is termed *eucrite* or, if it contains olivine in addition, *olivine-eucrite* ; the corresponding troctolitic variety, with olivine as the only essential ferromagnesian mineral, is known as *allivalite*. *Anorthosite* is the name applied to phanerocrystalline rocks which consist almost entirely of plagioclase feldspars (Plate III. 2). In general the feldspar is either labradorite or bytownite.

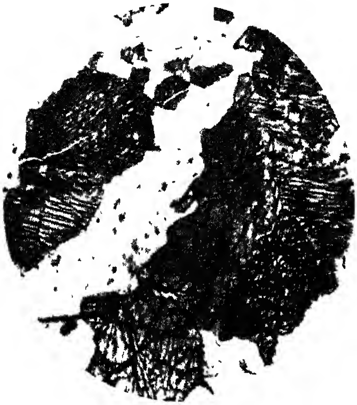
Gabbros are often more or less altered, the feldspars being changed to saussurite aggregates, the augite to uralite and the olivine to serpentine, talc, etc. When the feldspars are highly saussuritised the rocks are known as *saussurite-gabbro*. *Flaser-gabbro* is a term applied to gabbros which have been crushed and sheared and in which lenticular patches of the rock, still retaining their igneous character, are separated by layers of recrystallised material. *Orbicular gabbros* and *orbicular norites* have been described from a few localities.

Gabbros are all intrusive and occur as batholiths, bosses, sills, and dykes. They have a wide distribution both in space and time, ranging in age from pre-Cambrian to Tertiary.

Dolerites.—This term embraces all the rocks of medium texture which are the mineralogical equivalents of the gabbros. The texture is sometimes granular, but more typically it is ophitic or sub-ophitic, terms applied when some of the

PLATE XIV

MICROSCOPIC STRUCTURE OF MINERALS AND ROCKS



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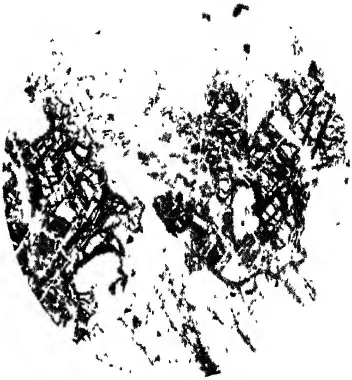

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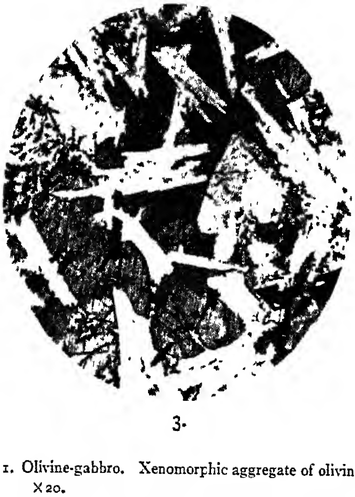

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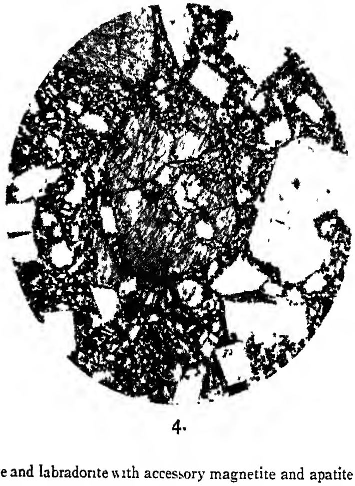


4.

1. Olivine-gabbro. Xenomorphic aggregate of olivine, diallage and labradorite with accessory magnetite and apatite ×20.
2. Troctolite. Xenomorphic aggregate of olivine (partly serpentinised) and labradorite, with accessory magnetite. ×20.
3. Olivine-dolerite, Hume Quarry, Berwickshire. Field occupied mostly by augite and labradorite in ophitic intergrowth; serpentinised olivine (bottom, right); accessory magnetite (black), patch of microcrystalline mesostasis (left). ×20.
4. Olivine-basalt. Phenocrysts of augite (centre), corroded and partly serpentinised olivine (right) and labradorite in a groundmass consisting of augite, labradorite and magnetite with some glassy base. ×20.

[*To face page* 53

labradorite is enclosed or partially enclosed in the augite (Plate XIV. 3). Usually the dolerites are even-grained, but occasionally they are porphyritic, showing phenocrysts of plagioclase, or, less frequently of olivine or pyroxene. They may be completely crystalline or they may show an interstitial or sometimes intersertal patchy development of glassy base or cryptocrystalline mesostasis. The chief constituents of *normal dolerite* are labradorite and augite with much accessory iron oxide and often apatite. The coming-in of olivine gives rise to a more common variety, *olivine-dolerite*. Of very frequent occurrence, too, are somewhat oversaturated types carrying primary quartz and named *quartz-dolerite*. The quartz is largely intergrown in micrographic fashion with orthoclase. When hypersthene accompanies the augite in quartziferous types the rocks are called *quartz-hypersthene-dolerite*. The term *tholeiite* is applied to dolerites and basalts which have a patchy, intersertal development of glassy base or mesostasis.

Dolerites are dark grey to black in colour when fresh. Owing to the abundance of chlorites and serpentine derived from the alteration of their ferromagnesian constituents, however, many dolerites have a dull greenish colour. The name *diabase* is sometimes used for such altered rocks in this country, but it should be noted that American geologists use this term for dolerites in general, while elsewhere it is a designation for pre-Tertiary dolerites. When dolerite sills have traversed carbonaceous shales, oil-shales, or coals they are sometimes transformed into a yellowish or white rock known locally as " white trap." Dolerites are widely distributed as minor intrusions.

Basalts, which are the aphanitic members of this series, are heavy, dark-coloured rocks, sometimes non-porphyritic, but more usually showing phenocrysts of one or more of the essential constituents. They are very often vesicular or amygdaloidal. Under the microscope it can be seen that the groundmass of basalts exhibits a wide range of textural variations. It will be sufficient here, however, to note that, while every gradation is found from holocrystalline to completely glassy types, the microcrystalline condition is by far the commonest. Not infrequently the augite and the labradorite are in ophitic or sub-ophitic relation to one another, and occasionally the plagioclase and augite form roughly spheroidal groups with internal radiating structure, thus giving what is known as *variolitic* structure. In *normal basalts* the essential minerals are augite and labradorite; magnetite is always abundant and is sometimes regarded as essential; apatite, as in all basalts, is a constant accessory mineral. With the coming in of essential olivine the rocks are named *olivine-basalt*, and this is the commonest type. Here olivine is normally a porphyritic constituent, and it may be accompanied by phenocrysts of augite or labradorite or of both these minerals (Plate XIV. 4). *Hypersthene-basalts* are not of very common occurrence, and *quartz-basalts* are still more rare. *Tachylyte* is a basalt-glass—sometimes compact and homogeneous, sometimes vesicular and carrying small phenocrysts. It occurs as the quickly cooled selvages of basalt and dolerite dykes and sills and as the slaggy portion of basalt lavas. Exceptionally it has been found to form the bulk of certain lavas. Basalts with variolitic structure are known as *variolites*.

Basalts are by far the commonest of lavas. From pre-Cambrian times to the present, in every successive period of vulcanicity, they have been extruded not only oftener, but in far greater volume than any other type of lava. They are also abundant as minor intrusive bodies such as dykes and sills. In the Columbia and Snake River region of North America basalt lavas cover an area of some 200,000 square miles. The basalts of the Deccan in India are equally extensive. The maximum thickness of the Deccan basalts is about 10,000 feet, and the average thickness about 2500 feet. Thick and wide-spread developments of basalt are met with also in Ireland and the Inner Hebrides, in Iceland, in Abyssinia, in Hawaii, and in many other parts of the world.

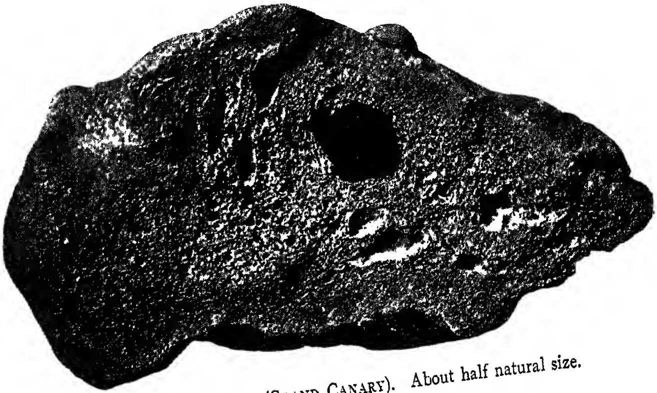
III. FELDSPATHIC ROCKS WITH ABUNDANT FELDSPATHOIDS

(a) The Nepheline Syenite-Phonolite Series.

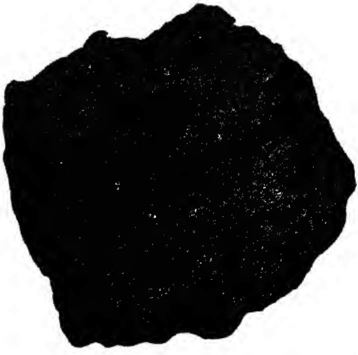
The coarse-, medium-, and fine-grained members of this series are respectively *nepheline-syenites*, *nepheline-micro-syenites*, and *phonolites*: the limits for grain-size are the same as in the syenite-trachyte series. They are characterised by the association of alkali feldspars and feldspathoids.

Nepheline-syenites.—These rocks are coarsely-crystalline aggregates of alkali feldspars (orthoclase, microcline, micro-perthite, cryptoperthite, albite), nepheline, and ferromagnesian silicates which are largely soda-amphiboles, soda-pyroxenes, and micas. Accessory minerals occur in great variety, and include sodalite, analcite, apatite, zircon, sphene, melanite, and several of the rare-earth minerals. The texture is sometimes granitoid, sometimes coarsely trachytoid, and a phenocrystic development of the light-coloured silicates is not

PLATE XV



1. Scoria or Cinder (Grand Canary). About half natural size.



2. Scoria or Cinder (Teneriffe). About natural size.

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uncommon. Nepheline-syenites are generally greyish or reddish in colour, and the nepheline (elæolite) is readily distinguished from the associated feldspars by its characteristic greasy lustre. They have the lowest density of all phanerocrystalline rocks.

Although nepheline-syenites are relatively rare a large number of varietal names has been applied to them. These have been based on textural characters, on the kind of feldspar present, on the nature of the ferromagnesian components, and in some cases on the presence as an essential mineral of some feldspathoid other than nepheline, e.g. *sodalite-syenite* and *analcite-syenite*. Fresh leucite is not known to occur in these rocks, but from a few localities there have been recorded rocks containing " pseudo-leucites "—aggregates of orthoclase, nepheline, etc., with outlines suggestive of leucite and supposed by some workers to be pseudomorphous after that mineral. Such rocks have been called *leucite-syenites* or given more specific names such as *borolanite*, a well-known rock from the Assynt district of Sutherland. The nepheline-syenite-pegmatites of Southern Norway are of particular interest because of the abundance and variety of the rare-earth and other unusual minerals which they contain.

Nepheline-microsyenites.—Examples of nepheline-microsyenites have been described under such names as *nepheline-syenite-porphyry*, *microfoyaite*, etc. *Nepheline-syenite-aplites* are medium-textured acid differentiates of nepheline-syenite magma.

Phonolites.—Under this name may be grouped all the aphanitic members of this series. They consist essentially of alkali feldspars (chiefly sanidine and soda-sanidine), feldspathoids, and soda-rich ferromagnesian silicates. Unlike their coarse-grained equivalents these rocks are often rich in leucite. Common accessory minerals are sphene, zircon, apatite, melanite, and feldspathoids other than those which are essential in any particular rock. *Normal phonolite*, which consists essentially of sanidine, nepheline, and a ferromagnesian silicate, commonly ægirine or ægirine-augite, is a compact, usually greyish or greenish rock, often with a waxy lustre, carrying sometimes phenocrysts of sanidine or very rarely of nepheline. In most cases it has well-marked platy jointing. Under the microscope the nepheline, in rocks in which it is very abundant, is recognised by the characteristic hexagonal transverse sections and short rectangular longitudinal sections (Plate II. 2); where less abundant the nepheline is normally interstitial and anhedral and less easy to identify, and in such rocks the structure of the groundmass resembles that of trachytes. Where leucite almost completely takes the place of nepheline the rocks are called *leucite-phonolites* by some authorities, *leucite-trachytes* by others. The latter use the name leucite-phonolite for a rock more generally called *leucitophyre*, in which the sanidine is accompanied by noteworthy amounts of both leucite and nepheline.

Where the nepheline is accompanied by large amounts of sodalite, haüyne, or analcite the rocks are known as *sodalite-phonolite*, *haüyne-phonolite*, and *analcite-phonolite* respectively. The phonolites occur both as lavas and as minor intrusions. Closely allied to the phonolites are the *tinguaites*, dense greenish rocks, which may or may not be porphyritic. Their distinctive characteristic is the very abundant development in the groundmass of needles of ægirine. They occur usually as dykes.

(b) The Theralite-Basanite Series

The rocks of this series are characterised by the association of basic soda-lime feldspars and feldspathoids. The coarse-grained types are rare, the commonest perhaps being *theralite* ; the medium-grained and fine-grained equivalents are of widespread occurrence and are typified by the *teschenites* and the *basanites* respectively. The limits for grain-size are the same as in the gabbro-basalt series.

Theralites are coarse phanerocrystalline rocks consisting essentially of augite, labradorite, and nepheline. Olivine is usually present. Common accessory minerals are orthoclase, analcite, ilmenite, magnetite, and apatite (see Plate II. 4). A few examples are known from the Carboniferous intrusions of Scotland. When primary analcite takes the place of nepheline we get the variety *analcite-theralite*.

Teschenites are medium-grained rocks with doleritic texture. They differ from olivine-dolerites mainly in their high content of analcite. The analcite occurs interstitially and as large "ocellar" patches and also to a considerable extent replaces labradorite. The chief ferromagnesian silicate is titanaugite, often surrounded marginally by ægirine-augite, and the pyroxene is usually in ophitic relation to the feldspar which is labradorite. Olivine, normally highly serpentinised, is very variable in amount. Common accessory minerals are orthoclase, zeolites, biotite, barkevikitic hornblende, iron ores, and apatite. Typical examples occur as sills of Carboniferous age in the Midland Valley of Scotland.

Basanites, the aphanitic members of this series, consist essentially of labradorite, monoclinic pyroxenes, olivine, and feldspathoids, chiefly nepheline, leucite, and analcite. Common accessory minerals are biotite, iron ores, sphene, and apatite. Soda-amphiboles, zircon, and chrome-spinels appear occasionally. In general the groundmass is microcrystalline and the rocks are porphyritic, but glassy varieties are found in thin lava-flows and in the marginal parts of lavas and minor intrusions. Basanites are ashy-grey to black in colour and are often vesicular or amygdaloidal. Varieties are named according to the dominance of particular feldspathoids, the most important being *nepheline-basanites*, *leucite-basanites*, and *analcite-basanites*. Nepheline-basanites and analcite-basanites resemble olivine-basalts in hand specimens, since nepheline and analcite do not appear as phenocrysts; the leucite-basanites, however, are readily distinguished from basalts by the presence of porphyritic leucites. Olivine-free basanites are known as *tephrites*. Leucite-tephrites and leucite-basanites are abundant as lava-flows and dykes at Vesuvius and other Italian volcanic centres. They are common also in East Africa, in the Dutch East Indies, and in Wyoming, U.S.A. The nepheline- and analcite-bearing types, however, are of much more frequent occurrence. Nepheline-basanite and analcite-basanite are met with as sills and lavas of Carboniferous age in Central and Southern Scotland.

IV. FELDSPATHOIDAL ROCKS FREE FROM OR POOR IN FELDSPARS

Included in this group are all rocks in which the only essential light-coloured silicates are feldspathoids, chiefly nepheline, leucite, and analcite. They are relatively rare in their occurrence, particularly the phanerocrystalline types, and the only rocks of the group that need be discussed here are the aphanitic nepheline-, leucite-, and analcite-rich varieties. These are all grey to black rocks, difficult to distinguish in most cases from basalts in hand specimens. They mostly occur both as lava-flows and as minor intrusive bodies.

Nephelinite is the name given to aphanitic rocks made up essentially of nepheline and monoclinic pyroxenes; when olivine is also essential the rocks are known as *nepheline-basalt* or *olivine-nephelinite*. They are mostly porphyritic and under the microscope the groundmass is seen to be usually microcrystalline, although glassy varieties also occur. Common accessory minerals include apatite, iron ores, basic plagioclases, and feldspathoids such as leucite, melilite, and sodalite. Types consisting essentially of leucite and monoclinic pyroxenes are called **leucitite** (see Plate II. 1), and, when olivine is essential, *leucite-basalt* or *olivine-leucitite*. In thin slices the groundmass of leucitites is seen to be microcrystalline with a sponge-like texture, augite prisms forming the walls and the clear rounded sections of the leucites simulating the holes of the "sponge." They are frequently non-porphyritic, but both leucite and augite may appear as phenocrysts. The leucite-basalts are usually porphyritic, showing phenocrysts of olivine and augite or, rarely, leucite; the groundmass may be microcrystalline or hypocrystalline. The usual accessory minerals in leucitites and leucite-basalts are apatite, iron oxides, and nepheline; others of fairly frequent occurrence are melilite, haüyne, nosean, and melanite. When analcite is the dominant feldspathoid corresponding types are **analcitite** and *analcite-basalt* or *olivine-analcitite*. Allied to the latter are the common lamprophyric dyke-rocks known as *monchiquites* (see Plate IV. 2).

V. ROCKS WITH NEITHER FELDSPARS NOR FELDSPATHOIDS ESSENTIAL

These are dark-coloured, heavy, ultra-basic rocks. The silica percentage ranges from 30 to 45 and the specific gravity from 3·0 to 3·3. Neither feldspars nor feldspathoids occur as essential minerals, the rocks consisting of varied combinations of the ferromagnesian silicate minerals or of these together with magnetite, ilmenite, and chromite. For the most part they are rather coarse-grained. Three main divisions of the phanerocrystalline types are recognised: *peridotites*, *perknites*, and *ores*. The aphanitic rocks are known as *limburgites*.

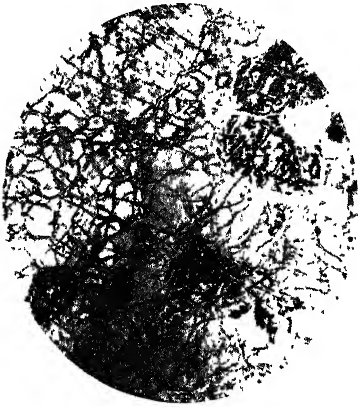
Peridotites.—These consist of aggregates of ferromagnesian silicates, one of which, as the name indicates, must be olivine. Rocks in which olivine is the only ferromagnesian silicate are known as *dunites* after Dun Mountain in New Zealand. Some examples contain as much as 98 per cent. of olivine, but in others there are considerable percentages of chromite, magnetite, and ilmenite. More usually, however, the olivine is accompanied by one or more of the common pyroxenes, amphiboles, or less often biotite. For such combinations a needless multiplicity of rock names has been used, based often on names of localities, but it is sufficient for our purpose to give mineralogical designations, indicating the dominating mineral or minerals which accompany the olivine. The chief types are *hornblende-peridotite* (Plate XVI. 1), *augite-peridotite*, *diallage-peridotite*, *hypersthene-peridotite*, *diallage-hypersthene-peridotite*, *hornblende-pyroxene-peridotite*, *hornblende-mica-peridotite*, and *mica-peridotite* (Plate XVI. 2). *Picrites* are types transitional to olivine-gabbros, carrying a varying, but always small, amount of basic plagioclase.

These olivine-rich rocks are often serpentinised, in most cases probably by late-magmatic hydrothermal agencies, and the massive *serpentines* (Plate XVI. 3) are mostly highly-altered peridotites.

Perknites.—Here are included phanerocrystalline rocks which are combinations of hornblende, augite, hypersthene, and biotite. Olivine is absent or merely accessory. The more important varieties are *hypersthenite*, *diallagite*, and *diallage-hypersthene-pyroxenite*, made up respectively of orthorhombic pyroxenes, monoclinic pyroxenes, and the two types of pyroxene in association. When much biotite accompanies the pyroxenes the rock is called *biotite-pyroxenite*. A variety consisting essentially of

PLATE XVI

Microscopic Structure of Minerals and Rocks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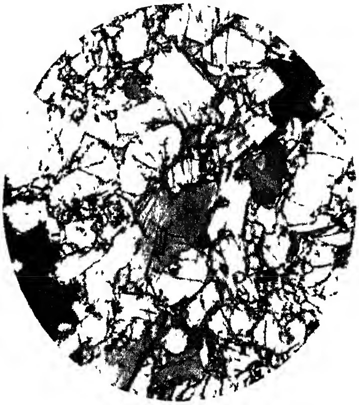
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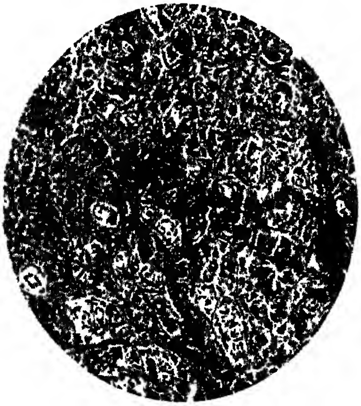
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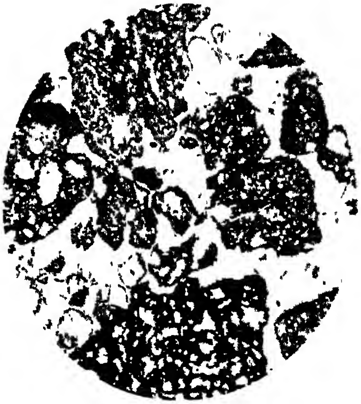

4.

1. Diopside-hornblende-peridotite, Schriesheim, Baden. Diopside (colourless) and olivine (serpentinised) enclosed poikilitically in a large crystal of hornblende. × 20.
2. Biotite-peridotite, Kaltes Tal, near Harzburg. Xenomorphic aggregate of olivine (large, white crystals) and biotite (large, grey to greyish-black); abundant accessory pleonaste-spinels (small colourless to grey crystals) and some ilmenite (black) × 20
3. Serpentine. Shows typical "mesh-structure." × 20.
4. Tuff. Fragments of vesicular glassy andesite and occasional grains of quartz; calcareous cement. × 20.

[*To face page* 58

hornblende is known as *hornblendite*. *Eclogite*, which is sometimes classified as a metamorphic rock, consists mainly of omphacite, a grass-green monoclinic pyroxene, and pink garnets; smaragdite, an emerald-green amphibole, is sometimes also abundant. Among the accessory minerals of perknites may be mentioned magnetite, ilmenite, chromite, olivine, garnets, pleonaste, apatite, and pyrites. The peridotites and perknites occur usually as relatively small intrusive bodies, very frequently as dykes; sometimes they are independent intrusions, sometimes parts of intrusive complexes.

Ores.—Magnetite, ilmenite, and chromite, which are often present in considerable amount as accessory minerals in peridotites and perknites, sometimes become the dominant constituents. Rocks made up chiefly of these minerals are known respectively as *magnetitite* or *magnetite-rock*, *ilmenitite*, and *chromitite*. They occur sometimes as independent intrusions, but are found more usually as local segregations in other basic and ultrabasic plutonic rocks.

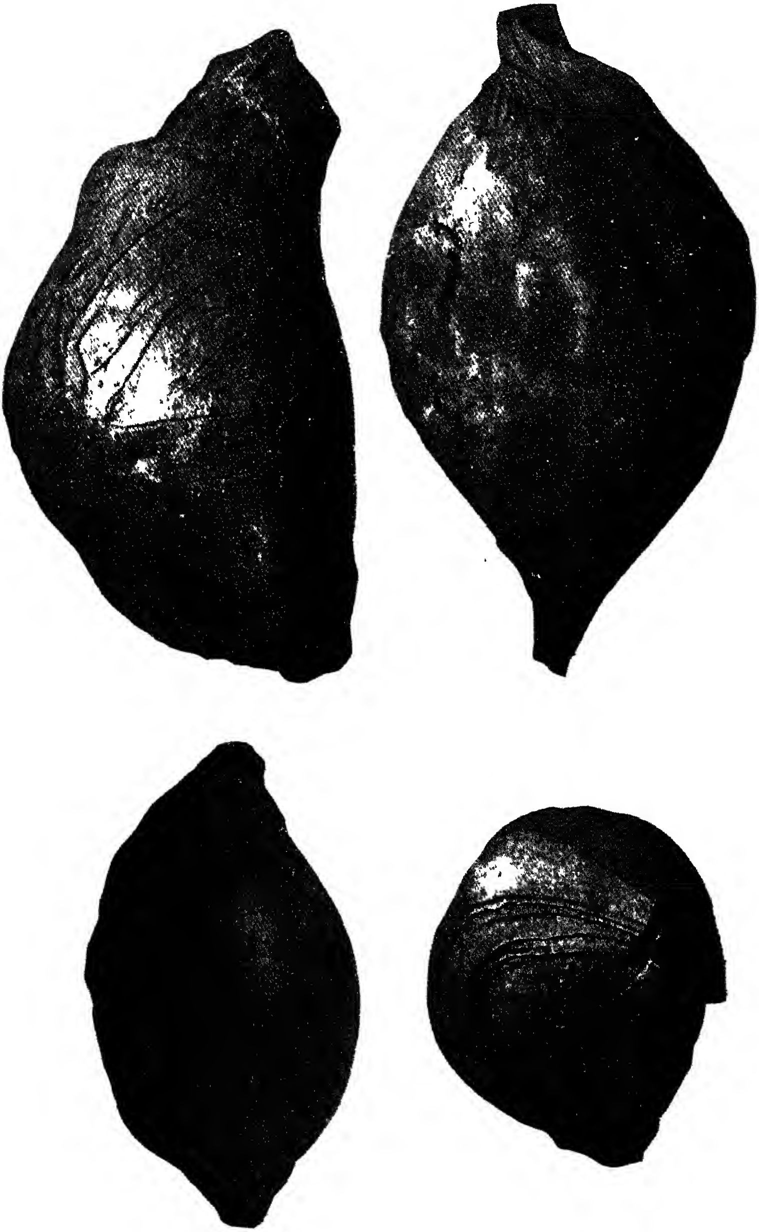
Limburgites are reddish-brown to black aphanitic rocks composed essentially of olivine and augite, usually with much magnetite and a variable amount of glassy base. Phenocrysts of olivine and augite are generally conspicuous, and in thin slices these are seen to be embedded in a glassy matrix containing smaller crystals and microlites of these minerals together with magnetite. Although they are often classified as the aphanitic equivalents of the peridotites, it is very doubtful whether this is true of many of the rocks to which the name limburgite has been given. The glass of the rock from the type locality, Limburg, in Baden, for example, contains so much potential nepheline and plagioclase that the rock is really a glassy variety of nepheline-basanite. The limburgites are difficult to distinguish from the monchiquites, which are equally rich in olivine, augite, and iron ores but have analcite in place of the glassy base of the limburgites.

B. Fragmental Igneous (Pyroclastic) Rocks

These rocks include the various kinds of material which have been ejected from volcanoes in the form of blocks, scoriæ, lapilli, bombs, sand, and ash. **Blocks** and **Lapilli** are the names given to the larger and smaller rock-fragments, which may be angular or subangular; while the finer-grained materials are known as **Sand** and **Ash.** **Scoriæ** are loose pieces of cindery lava (Plate XV.). **Bombs** are elliptical or pear-shaped fragments, often vesicular or hollow (see Plate XVII.). They are simply clots torn from the surface of a mass of molten rock by the explosive energy of steam, and ejected from the crater of a volcano, their form being doubtless the result of their rotatory motion. Accumulations of these and other kinds of volcanic ejecta frequently become indurated, and are met with in regular and irregular beds associated with crystalline igneous rocks of all geological periods. **Volcanic Agglomerate** is the name given to a coarse admixture of large and small blocks and stones set in a matrix of comminuted rock débris and grit, which may be either abundant or meagre. Frequently, this rock is found occupying the pipes or throats of ancient volcanoes—the upper portions of which have been denuded away. **Volcanic Breccia** is a mass composed of angular fragments of volcanic rock. **Volcanic Tuff** is the name given to aggregates of the finer-grained ejectamenta (Plate XIII. 2). These are often arranged in layers and beds which have been spread out by water action. There are endless varieties of structure and texture—some tuffs consisting of lapilli, or of grit, or of sand and ash ; others made up of all four, and not infrequently arranged in lenticular layers and beds. Some volcanic tuffs consist of the finest ash-like material, forming a dull, fine-grained, or compact rock, which varies in colour from white or grey to darker or lighter shades of red, green, yellow, etc.

As tuffs are composed almost exclusively of fragments and the comminuted débris of lava, they naturally differ in character according to that of the effusive rocks with which they are associated. Hence we have *basalt-tuff*, *andesite-tuff*, *rhyolite-tuff*, etc., any of which may of course contain a large or small proportion of fragments and débris of derivative rocks or of metamorphic or plutonic rocks, as the case may be. Most frequently, however, the fragments are entirely volcanic.

PLATE XVII



Volcanic Bombs. Cinder Buttes, Idaho

From *Bull. U.S. Geol. Survey*, No. 199

[*To face page* 60

CHAPTER IV

ROCKS—*continued*

Classification of Derivative Rocks:—I. Mechanically formed Rocks, including Subaërial and Æolian, Sedimentary, and Glacial Rocks (Soil and Subsoil, Rock-rubble, Rain-wash, etc., Blown Sand and Dust, Laterite, Terra Rossa, Conglomerate, Grit and Sandstone, Greywacké, Clay, Till, etc.). II. Chemically formed Rocks (Stalactites and Stalagmites, Tufa, Dolomitic Limestone, Rock-salt, Gypsum, Siliceous Sinter, Flint, etc., Ironstones). III. Organically derived Rocks (Limestone, Siliceous Rocks, Carbonaceous Rocks, Bituminous Rocks, Phosphatic Rocks).

II. DERIVATIVE ROCKS

THE rocks included under this head are of very diverse origin, and show great variety of composition, texture, and structure. Some are dominantly siliceous, calcareous, argillaceous, ferruginous, or carbonaceous; others are mixtures of many different kinds of material; while a few are composed of one mineral substance only. As regards texture, they vary from smoothly compact rocks to aggregates of the coarsest kind. So, likewise, they exhibit much variety of structure—the large majority consisting of fragmental (clastic) materials, while not a few are crystalline or sub-crystalline. All derivative rocks are of *epigene* origin, *i.e.* they have been produced at or near the surface of the earth by the action of the various superficial agents of change—wind, rain, frost, running water, etc. Hence many have been formed mechanically; some are due to chemical action; while others are of organic origin. As a rule they are characterised by a more or less pronounced bedded arrangement, and thus are often termed collectively the "Stratified Rocks." Furthermore, as water has played the most important part in their formation, they are not infrequently spoken of as the "Aqueous Rocks." As some, however, show no trace of aqueous action, while certain others are not stratified or arranged in layers, we may designate the class by the more comprehensive term of **Derivative Rocks.** For, as we shall learn, all the rocks in question are composed of materials derived from the breaking up and disintegration of pre-existing minerals and rocks by epigene agents, and from the débris of plants and animals.

Various systems of classification have been adopted for the Derivative Rocks, none of which can be said to be quite satisfactory. Perhaps as convenient a system as any is that which is based on the geological origin of the various rocks. At all events, it has the merit of directing the student's attention to the action of the various epigene agents of change which are so ceaselessly employed in modifying the crust of the globe. We shall therefore group the series under these three heads: MECHANICALLY FORMED, CHEMICALLY FORMED, and ORGANICALLY DERIVED Rocks.

I. Mechanically formed Rocks

The vast majority of these rocks consist of fragmental materials—they are, in short, aggregates of fragments of minerals and rocks. Some of them are due to "weathering" and the action of wind; others are the products of the action of moving water; while yet others are the result of the action of ice. We have thus three types of mechanically formed derivative rocks, namely, 1. *Subaërial and Æolian Rocks*, 2. *Sedimentary Rocks*, and 3. *Glacial Rocks*.

1. SUBAËRIAL AND ÆOLIAN ROCKS

Under this head are included all accumulations which are due to "weathering" and the action of wind. The process known as "weathering" is by no means, however, exclusively mechanical. The subaërial disintegration of rocks is brought about by the operation of various agents, and it is not always possible to assign to each its proper share in the work performed. In cold regions, rocks are broken down chiefly by the action of frost; in many temperate countries the chemical action of rain is often the most effective agent of destruction, or the work of demolition may be pretty equally divided between rain and frost; while in hot and dry deserts, rocks crumble away mainly under the influence of *insolation*—they expand when heated up during the day, and contract more or less rapidly at night, and thus their constituent ingredients lose cohesion and the rocks become disintegrated. Some or all of these operations, it is obvious, may be carried on concurrently, almost anywhere, so that it is usual to include them under the general term of *weathering*. Of subaërial and æolian rocks, the most important are the following :—

Soil and **Subsoil.**—The particular origin of these will be fully discussed in Chapter XXIV., and they need only be shortly defined at present. *Subsoil* is an unconsolidated heterogeneous aggregate of disintegrated rock-material; while *Soil* is essentially the same, with the addition of organic matter.

Rock-rubble is the general term applied to collections of angular fragments which owe their origin chiefly to the action of frost in high northern and temperate regions, and mainly to insolation in low latitudes. Familiar examples are the taluses of stony débris which gather at the base of precipice and scaur, and the sheets of angular rock-rubbish which curtain the hill-slopes of our mountain areas. A rubble of angular fragments formed in this way, if cemented together, would be called *Scree-breccia*. [There are many kinds of breccia—this term being qualified in each case by some adjective descriptive of its origin or the character of its dominant components.]

Rain-wash, Brick-earth, etc.—In this and other temperate regions the finer-grained material derived from the disintegration of rocks by weathering is gradually washed down by rain from higher to lower levels, and tends to accumulate on gentle slopes and in hollows. This rain-wash is occasionally sufficiently fine-grained and plastic to serve for brick-making purposes (*brick-earth.*) But rain-wash may, on the other hand, consist of very coarse materials. In some countries where the rainfall is crowded into a short space of time, sudden torrential rains sweep the steeper declivities of the land bare of rock-débris, and spread the materials over the low-lying tracts that extend outwards from the hills and mountains. The stones included in such accumulations are more or less angular, having travelled usually no great distance.

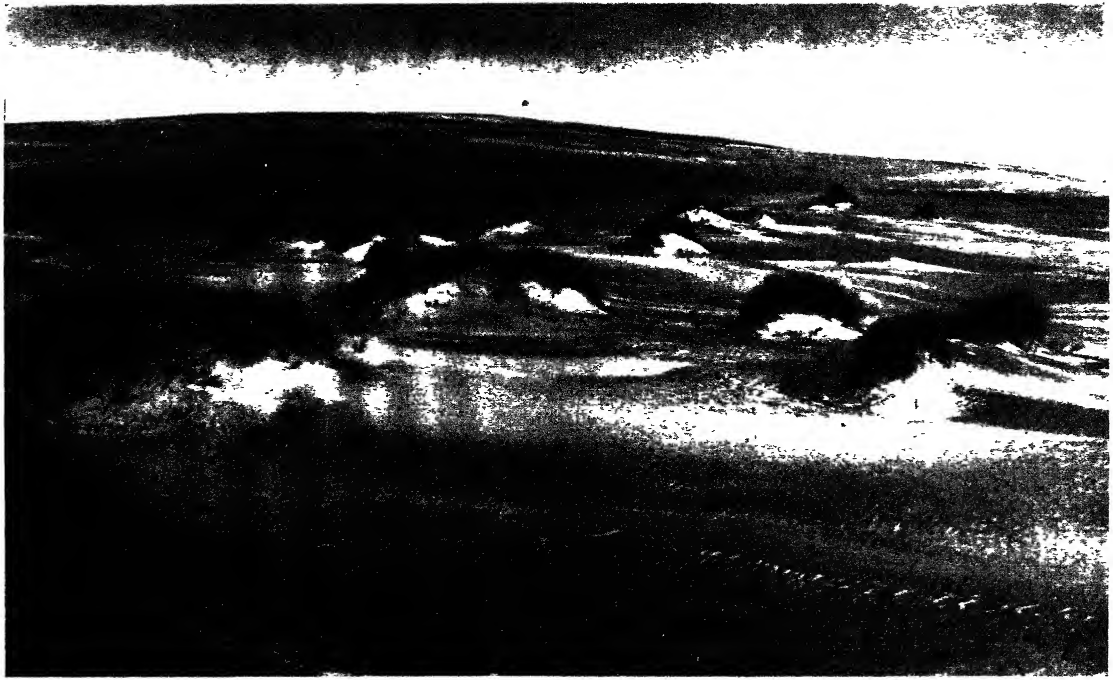
Besides rain-wash and brick-earth there are various other products of the weathering of rocks, but these will be considered later on when we come to discuss the nature and origin of soils and subsoils.

Laterite is the name given to the porous or cellular "clays," of dominant red or brown colour, which are characteristic products of rock-weathering in tropical and sub-tropical countries. Unlike ordinary clay, which consists for the most part of hydrated silicates of alumina, laterite is essentially a mixture of hydrated oxides, chiefly of iron and aluminium. It ranges from highly ferruginous to highly aluminous, and usually carries varying amounts of ordinary clay and quartz sand. It is often relatively rich in oxides of manganese, and these, as well as the iron oxides, may be segregated to form concretions. Laterite is readily dug up, but becomes very hard when dried. Much of the laterite of India, which was the first to be described, is found overlying basalts, but, under suitable climatic conditions, it occurs as a product of subaërial decomposition of various other rocks such as gneiss, mica-schist, and other crystalline schists, slates, certain sandstones, and many kinds of eruptive rocks.

Terra rossa is a red or brownish ferruginous earth met with more or less abundantly in regions composed of limestone and calcareous rocks. It is simply the insoluble residue derived from the dissolution of these rocks by atmospheric action. It assumes a great development in the limestone regions of southern Europe, but may occur wherever such rocks are exposed to the action of the weather. The red earth, so frequently met with in limestone caves, is of the same origin, and has been introduced for the most part by rain and melting snow, through fissures communicating with the surface.

Blown Sand and Dust.—*Blown Sand* accumulates under all conditions of climate—wherever, indeed, loose sand is exposed to *deflation* or the transporting action of the wind. Hence dunes and sheets of wind-blown sand are well developed upon certain sea-coasts (Plate XVIII.) and lake-shores, and in the broad, flat valleys of many large rivers. In such regions the wind acts chiefly as a transporter of disintegrated rock-material—the sand having already been prepared for it by the action of other superficial agents, such as tidal currents, waves, rivers, etc. In dry, desert tracts, however, blown sands owe their origin and distribution mainly to the combined action of insolation and deflation. By alternate expansion and contraction rock-surfaces are broken up and comminuted, and the grit and sand thus formed are carried forward by the wind. This loose material, swept against upstanding rocks, acts as a kind of sand-blast which abrades, frets, honeycombs,

PLATE XVIII



SANDHILLS, CULBIN, MORAYSHIRE

[In the background an advancing dune. Direction of wind shown by tails of sand behind tufts of "bent" grass, and by rippled surface in foreground.]

[*Photo, H.M. Geological Survey*

[*To face page* 64

and undermines them—in other words, the sand that results from the action of insolation grinds and reduces to sand and dust the exposed rock-surfaces against which it is borne. As the travelling sand-grains, which seldom rise more than a few feet above the surface, are continually subject to mutual attrition, both in the air and upon the ground, they tend to become more or less well rounded (Plate XXI. 2). This character often serves to distinguish desert-blown sand from sand of alluvial origin—the smaller grains of which are rather angular or subangular in shape. Having been carried mainly in suspension, they escape the constant trituration to which the grains of blown sand are subject. Blown sand, as a rule, consists principally of quartz—the commonest and one of the hardest of rock-forming minerals. In coastal tracts, however, the dunes, while consisting chiefly of quartz, often contain many other ingredients, more especially comminuted shell-débris. Further, the grains of coastal-blown sand are not infrequently coarser and less well rounded than those of desert sand.

Dust is pre-eminently a product of relatively dry regions and of deserts—wherever, indeed, the land is naked or only partially clothed with vegetation, dust is formed, and may be swept up and transported by the wind. While the blown sand of a desert rises only a few feet or yards above the ground, the powdery dust is often swept upwards to a great height, and may be transported for hundreds or thousands of miles from the place of its origin. The fine-grained, homogeneous, calcareous, and sandy loam known as *Loess*, which occupies wide areas in middle and south-eastern Europe, and covers vast tracts in China, is supposed by many geologists to be essentially a dust deposit or "steppe formation."

2. SEDIMENTARY ROCKS

The rocks included under this head owe their origin to the mechanical action of water, and are usually, therefore, arranged in layers or beds. They vary exceedingly in texture—from coarse aggregates of boulders and shingle to sediments composed of the finest impalpable materials. Less sharply distinguished from each other, as a rule, than is the case with igneous rocks, sedimentary rocks of various kinds often merge into one another—coarse-grained grits and sandstones, for example, passing gradually into the finest argillaceous accumulations. The coarser-grained accumulations are almost invariably of shallow water origin—deposited at or opposite the mouths of rivers and along the seashore between low and high-water levels. The medium grained masses have been laid down generally in somewhat deeper water—or in places where aqueous action was less strenuous. The finest grained sediments have accumulated in still water, and therefore usually at some distance from the land. Such being the origin of sedimentary rocks, it is not surprising that they should frequently contain the relics of animals and plants, *i.e.* fossil organic remains.

Conglomerate is a bedded or amorphous aggregate of water-worn stones, and may be either of marine or freshwater origin. It is, in short, simply a more or less consolidated gravel. The matrix in which the stones are set is usually gritty or sandy, and may be scanty or abundant. The rock often graduates into *pebbly grit* and *conglomeratic sandstone.* The cementing material may be siliceous, calcareous, argillaceous, or ferruginous. Quartz, compact siliceous sedimentary rocks and crystalline igneous and metamorphic rocks are conspicuous components of conglomerates. *Aqueous Breccia* is a consolidated rock-rubble, which has been accumulated in water.

Grit and **Sandstone.**—These are simply coarser and finer grained varieties of one and the same kind of rock—namely, compacted or cemented grit or sand. The most abundant component is usually quartz, but many other ingredients may be present. Amongst these may be muscovite, feldspar (more or less kaolinised), composite rock fragments, and occasionally some of the less readily decomposed accessory minerals derived from the disintegration of igneous and schistose rocks, such as zircon, schorl, garnet, apatite, magnetite, ilmenite, etc. The finer grains of an aqueous sandstone, unlike those of desert sand, are often angular or subangular (Plate XXI. 1), while the larger grains and small pebbles are usually well waterworn and rounded. Sandstones may be white, grey, yellow, brown, red, greenish, or black. The colouring matter is in most cases due to that of the cementing or binding material, which may either be dispersed between the grains, as in carbonaceous sandstones, or appear as thin pellicles or skins enveloping the individual particles. White and light grey sandstones and grits may have a calcareous, or argillaceous or siliceous binding material, or they may have been compacted by pressure alone. Yellowish and brownish colours are due, for the most part, to ferric hydrate, and red colours to hæmatite (ferric oxide), while greenish hues frequently indicate the presence of some impure hydrous silicate of iron and other bases.

Varieties:—*Freestone* or *Liver-rock*, a fine-grained homogeneous sandstone capable of being tooled equally well in any direction. *Flagstone*, a thin-bedded, fine-grained sandstone, which separates readily along the bedding-planes, frequently more or less argillaceous, and often micaceous. *Micaceous sandstone*, fissile, usually fine-grained, with abundant scales of white mica. *Greensand*, a sandstone of a dull greenish colour, owing to the presence of disseminated glauconite. *Grit*, simply a coarse-grained sandstone. *Arkose*, a grit composed of quartz, feldspar, and mica; derived directly from the disintegration of granite or gneiss.

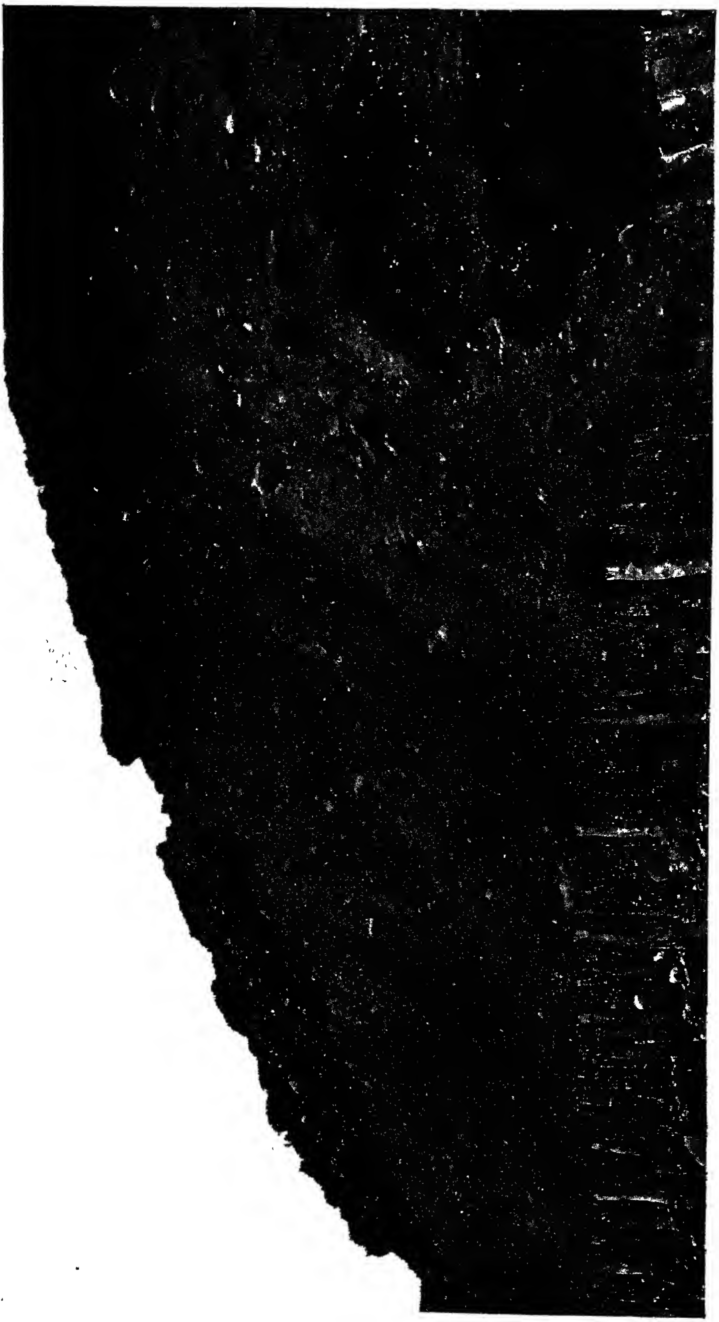
Greywacké is a more or less indurated rock, composed of rounded, subangular, and often sharply angular grains of quartz, feldspar, basalt, andesite, and other minerals and rocks, amongst which scales of mica are not infrequently conspicuous. Besides such grains, greywacké usually contains in less or greater abundance flakes and splinters of various compact rocks, such as slate, hornfels, lydian-stone, felsite, etc. The cementing material is usually meagre and often siliceous, but it may be argillaceous, chloritic, calcareous, or ferruginous, or even anthracitic. Grey and blue are the commonest colours of the rock, but green, brown, red, purple, yellow, and even black varieties occur. The texture varies from compact and fine-grained to coarse-grained and brecciated. The rock occurs in thin layers and massive beds which often show graded bedding, interstratified with slaty shales and slates, and is practically confined to the older geological systems (Palæozoic).

Clays.—These are aggregates of very finely divided mineral matter, which become plastic when moistened. The finer varieties appear to the unassisted eye quite homogeneous, and when squeezed between the fingers have an unctuous feel, and seem as if composed of some impalpable substance. With the exception of kaolin, however, clays are really heterogeneous aggregates of various minerals and different kinds of rock material.

Two distinct varieties of common clay are recognised—namely, *alluvial clay* and *glacio-aqueous clay*. In *alluvial clay* the finer grained constituents are obviously the result of the chemical decomposition of minerals and rocks, and consist largely of hydrous silicates of alumina. Disseminated through this material occur minute grains of quartz, and frequently fine flakes of pale or colourless hydrous mica. Other constituents present in ever-varying proportions are iron-oxides and carbonates of calcium, magnesium, and potassium. Clays of this character are invariably of secondary origin: they have been derived from the disintegration and decomposition of rocks, partly a mechanical but largely a chemical process. They consist, in short, chiefly of the insoluble residue of rocks. *Glacio-aqueous clay*, on the other hand, owes its origin mainly to the mechanical grinding and pulverising of rocks by glacier-ice, and consists therefore chiefly of fine rock-flour or rock-meal reassorted and deposited in water without having undergone much chemical alteration. When clays of this character are microscopically examined, we find not only abundant grains of quartz and flakes of relatively fresh mica, but particles of many other minerals, such as various feldspars and other silicates, all more or less fresh and chemically unaltered. The proportion of hydrous aluminium-silicate present is much less than in the case of clays of alluvial origin. It is generally assumed that the hydrous aluminium-silicate in clays of all kinds is kaolin, but this has not yet been demonstrated. The common belief that the plasticity of clays is due to the presence of the hydrous silicate in question is even more doubtful. Almost any rock-forming silicate—nay, quartz itself, if reduced by grinding and rubbing to the consistency of an impalpable powder—becomes plastic when moistened, and has the earthy odour of clay.

Varieties of Clay.—*Kaolin* is a product of the decomposition of highly feldspathic rocks (granite, gneiss, etc.). The purer kinds of kaolin occur *in situ*—*i.e.*, they occupy the site of the altered rock, and probably owe their origin to the action of heated solutions and vapours coming from below. When kaolin has been washed away from its place of origin and deposited elsewhere it is never so pure as that which has not travelled, but is often mixed with many other ingredients. The purest kaolin is a silvery white powder consisting entirely of very minute six-sided plates of the mineral kaolinite—a hydrous silicate of alumina with a definite chemical formula ($H_4Al_2Si_2O_9$). When moistened, this aggregate of scaly kaolin, or *Kaolinite*, is plastic. The *Kaolin* or *China-clay* of commerce, however, usually contains many impurities; it is rather a rock than a mineral. *Pipeclay* is a fine white clay which shrinks too much on the application of heat to be available for pottery-making. It contains a larger percentage of siliceous matter than kaolin. *Fire-clay* is a clay containing little or no lime, alkaline earths, or iron, which act as fluxes. It is thus infusible or highly refractory, and suitable for bricks, etc., which are required to stand intense heat. *Brick-clay* is an intimate admixture of clay and sand with some iron-oxide, and is used for ordinary bricks. *Fuller's earth* is a soft, dirty greenish, brownish, blue, yellow, or grey variety of clay, somewhat greasy or unctuous to the feel, which falls into powder in water. *Shale* is the name given to any argillaceous rock that divides into thin layers or laminæ, corresponding to planes of deposition. Shales vary greatly in composition, some containing much sand (*arenaceous shale*), others being largely carbonaceous (*carbonaceous shale*). *Alum shale* is an argillaceous rock charged with a considerable quantity of

PLATE XIX



Boulder Clay, Brownhead, South Arran.

Photo by H.M. Geological Survey.

[*To face page* 69

disseminated pyrite or marcasite (sulphides of iron), through the decomposition of which alum (sulphate of alumina) and copperas or iron vitriol (hydrous sulphate of iron) are formed.

Loam is a mixture of sand and clay, usually containing some calcium-carbonate and organic matter, the sand being plentiful enough to allow the percolation of water through the mass. Most loams are of alluvial origin, and are, therefore, commonly developed in valley-bottoms.

3. GLACIAL ROCKS

These rocks are the result of the mechanical action of ice. *Rock-rubble*, already described as a subaërial formation, might perhaps be classed as a glacial rock, since it owes its origin chiefly to the action of frost. It is preferable, however, to include here only those formations which are the products of glacial erosion and transport. Among these, by far the most important is **Boulder-clay** or **Till** (Plate XIX.), a more or less tenaceous, gritty clay, crowded with angular and subangular stones and boulders, many of which are polished and striated. It varies, however, very much in character, being occasionally more arenaceous than argillaceous. When the larger stones are removed it is often used for brick-making; in many cases, however, it is too stony for such a purpose. Boulder-clay, unlike alluvial clays, is not bedded or stratified; it represents the bottom- or ground-moraine of glaciers and ice-sheets. Consolidated boulder-clay is known as *tillite*. [See also p. 302.]

When subjected to mechanical analysis, the plastic materials of the till of the Scottish lowlands is seen to be a heterogeneous aggregate of minutely triturated mineral matter, and much rock-flour of a very fine consistency. Only a meagre proportion of this so-called "clay" consists of hydrous silicates of alumina, or pure clay. Boulder-clay, in short, is composed for the most part of unweathered rock-material—it is the result of glacial grinding, and has not, like ordinary alluvial clay, been formed by the chemical decomposition of minerals and rocks.

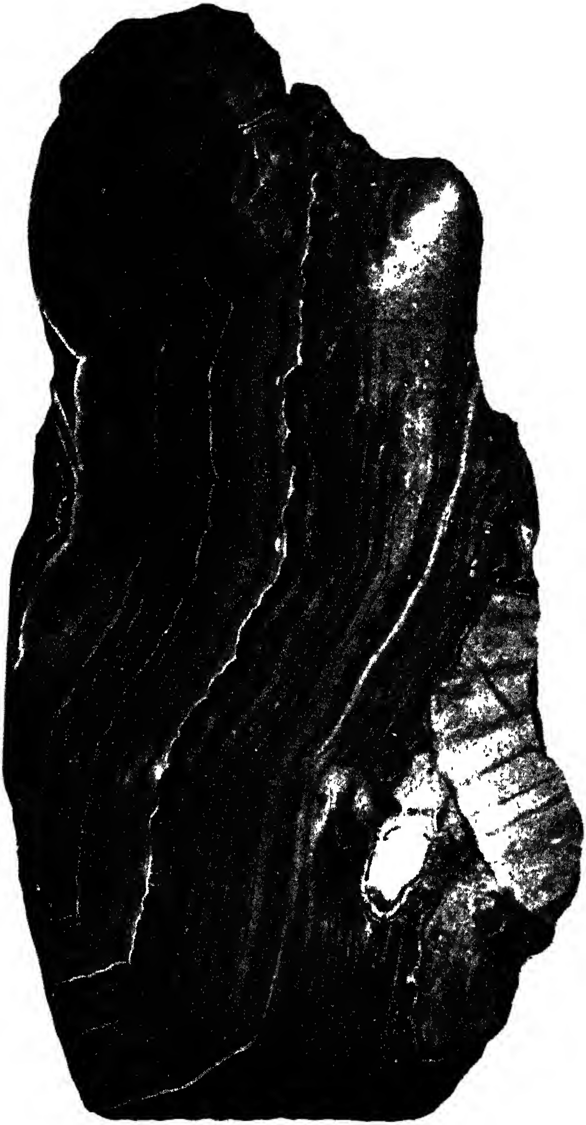
The only other glacial accumulation that need be referred to are the mounds and sheets of earthy rock-débris and boulders which occur in and opposite the mouths of many of our mountain valleys. These have been transported by the glaciers of the Ice Age as superficial *moraines*, some of the more conspicuous heaps having been dumped down as terminal moraines during long pauses in the final retreat of the old ice-flows, while hummocky sheets of the same materials were gradually spread over the flanks and bottoms of our mountain valleys as the glaciers melted more or less rapidly away (see Plate LXIV.).

II. Chemically formed Rocks

These are for the most part chemical precipitates from aqueous solutions, and are chiefly calcareous, siliceous, ferruginous, and saline. Some have been deposited at the surface as the result of evaporation; others are precipitates from saturated solutions, and have thus accumulated on the floors of salt-lakes and seas. Again, a few are of the nature of aggregations: originally diffused through the rocks in which they occur, they have since drawn together and become concentrated so as to form nodules and nodular masses or independent layers.

Stalactites and **Stalagmites.**—These are precipitates from water holding calcium carbonate in solution. They are of common occurrence in limestone caverns, the stalactites growing downwards from the roof and the stalagmites slowly accumulating on the floor. Carbonated water percolating through the limestone oozes out on the roof of a cavern, and, being there exposed to evaporation, is compelled to part with some of its calcium carbonate, which adheres to the rock-surface. When the gathering drop of water falls to the ground it is there again exposed to evaporation, and gives up the remainder of the carbonate which it held in solution. The colour of these deposits varies indefinitely—they may be creamy-white, yellowish, brownish, or reddish, and are often mottled. They usually show a concentric, laminated structure, and the stalactites, in the early period of growth, are porous and readily crushed; subsequently, however, their pores become filled up with calcium carbonate, and the structure thus gradually solidifies. Stalagmites are seldom or never so porous, but exhibit a well-defined laminated structure (see Plate XX.). In course of time both stalactites and stalagmites, owing to molecular changes, tend to acquire a crystalline structure.

Tufa or Calc-sinter is formed by deposition from calcareous springs. It is a porous and frequently very friable compound of calcium carbonate. The colour varies; creamy-white and yellow tints are common, but red and brown are not infrequent, while some kinds are greenish or bluish. The rock is often mottled or marked with concentric bands of different colours. *Travertine* is the name given to compact varieties used for building-stones. They have frequently a crystalline or sub-



STALAGMITE, GIBRALTAR. Nearly natural size.

[*To face page* 70

crystalline structure. Some tufas and travertines consist largely of small spherules of calcium carbonate, composed of concentric layers which have been deposited successively around some nucleus, such as a particle of sand or a minute fragment of calcareous matter. When the spherules are small, resembling fish-roe, the rock is termed *Oölite* ; when they are of the size of peas it is known as *Pisolite*.

Many interstratified common limestones, consisting of fine-grained crystalline aggregates of calcite, are of chemical origin. There are numerous varieties characterised by the presence of certain impurities and admixtures. *Cornstone*, for example, is a highly calcareous sandstone or arenaceous limestone ; *cementstone* is a dull argillaceous and sometimes ferruginous limestone, often occurring in thin beds and layers in the same way as clay-ironstone, and sometimes used for making hydraulic cement ; *carbonaceous limestone* contains much carbonaceous matter, and limestones of this kind often emit a fetid odour when rubbed or struck with a hammer.

Dolomites and **Dolomitic Limestones** are crystalline granular aggregates, the former composed of the mineral dolomite alone, the latter of calcite and dolomite. They effervesce only slightly with cold dilute hydrochloric acid, but are readily attacked when the acid is heated. Ferrous carbonate and various impurities are more or less commonly present. When such is the case the rock is usually yellowish ; when impurities are only sparingly present it is grey or white. It frequently assumes a concretionary structure, showing botryoidal and irregularly shaped masses, or appearing as if built up of spherical bodies that may vary in size from small marbles up to large cannon-balls. Lines of bedding pass through these curious concretions. Many irregular cavities appear in dolomite, and these are often lined with crystals of bitter-spar. Typical dolomite is easily distinguished from ordinary limestone by its superior hardness (3·5 to 4·5), its greater specific gravity (2·8 to 2·9), and its much less ready solubility in cold acid.

Some dolomites, especially those which are associated with beds and layers of rock-salt and gypsum, may be of the nature of chemical precipitates on the floors of salt-lakes, lagoons, and other bodies of highly saline water. Many, however, would appear to have been originally common limestones, which, either at the time of their formation or subsequently, have by various chemical processes been converted into dolomitic limestones. Few limestones are without some proportion of magnesia, so that it is not possible to draw a hard-and-fast line between common limestone and magnesian limestone—a term applied to limestone free from domolite but containing notable percentages of magnesium carbonate in solid solution in the calcite. Between this and limestones which contain little or no magnesia there are all gradations.

Rock-salt is a crystalline, fibrous, or even granular aggregate of sodium chloride, which occurs either in thin layers or in massive beds, sometimes reaching a thickness of several hundred feet. When pure it is clear and colourless, but it is often stained with impurities, being frequently red, yellow, or grey. Blue and green tints also occur, but they are not common. The mineral is frequently turbid owing to admixture with sandy or argillaceous matter. In many places, indeed, it passes into a saliferous clay. It is usually associated with gypsum, anhydrite, and dolomite, interstratified with clay, marl, and red or particoloured sandstones, and has obviously been deposited in salt-lakes or in arms of the sea more or less cut off from the general body of open water.

Gypsum, hydrous calcium-sulphate, occurs in beds, layers, or lenticular sheets and masses, and is often associated with rock-salt, anhydrite (calcium sulphate), dolomite, red clay, and sandstone, etc. In structure it varies from compact to granular, or it may be a fibrous, scaly, or sparry aggregate. When relatively pure it is white or quite colourless, but is often stained yellow or red by iron-oxides, or coloured grey and brown, owing to admixture with clay or other impurities. The exceedingly fine-grained varieties are known as *Alabaster*. Compact gypsum is readily distinguished from limestone, which it sometimes resembles, for it is scratched by the finger-nail, while limestone is not.

Siliceous Sinter is an aggregate of amorphous silica containing a variable proportion of water. It may be loose, unconsolidated, and porous, or dense and compact, and often assumes stalactitic and stalagmitic forms. When free from impurities it is white, but as these are often present it may be stained various shades of yellow or red. It is formed by deposition from thermal springs as the result of evaporation; in some cases, however, deposition is partly due to the action of minute algæ, which occasionally flourish in the hot pools of a geyser region.

Flint is a hard grey or black rock, composed of amorphous or chalcedonic silica—the dark colour being due to carbonaceous matter. It breaks with a marked conchoidal fracture, and is translucent along the sharp cutting edges. Its most characteristic occurrence is in the form of nodules, layers, and vertical ramifying or vein-like masses in white chalk.

Its precise mode of formation is not quite clear, but it would appear to be partly of organic, partly of chemical, origin. Sponges and other organisms secrete soluble silica from sea-water, and when they die additional silica is deposited upon and within their skeletons and exuviæ. Calcareous shells, and even the chalk itself in which these are embedded, have often been partially or wholly replaced by silica, so that silica in a soluble form must have been diffused to some extent through the calcareous ooze of Cretaceous seas. Probably the silica was largely derived from the skeletal remains of sponges, which flourished in great abundance during the formation of the chalk. *Chert* is a somewhat impure kind of flint, of not uncommon occurrence in limestones belonging to the older geological systems (Palæozoic), and, like it, probably partly of organic, partly of chemical, origin. In some cases, however, it possibly represents the deposits of thermal springs. *Hornstone* is a somewhat similar rock; it is more brittle than flint. *Lydian-stone* is a mixture of silica and clay, usually with carbonaceous or ferruginous matter. It is black, purplish-red, or dark blue, very hard and compact, and often much cracked and rent, the small fissures being usually filled with white quartz. It occurs in thin beds and layers in the older Palæozoic systems, and in some cases, at least, contains remains of radiolaria (*Radiolarian Chert*), so that such rocks may represent the radiolarian oozes of ancient seas (Plate XXI. 4).

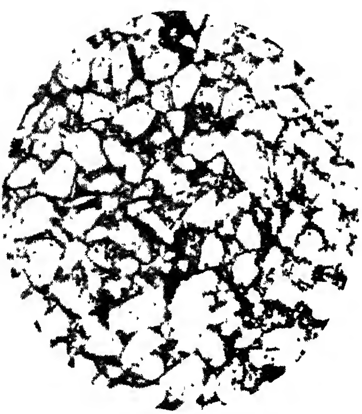
Ironstones are sometimes of chemical, sometimes of organic, origin, or partly both. Occasionally they occur in the form of beds or layers interstratified with other derivative rocks, or of nodules and nodular masses embedded chiefly in argillaceous deposits. They are frequently met with also occupying fissures and irregular cavities. *Limonite*, when approximately pure, is a compact fibrous or stalactitic aggregate, in which form it usually occurs in veins and cavities. When appearing as a bedded rock it is usually earthy and porous, and crowded with impurities. It forms the hardpan which so frequently appears under marshy ground (*Bog Iron-ore*), and often occurs as a lacustrine formation in layers of small spherical bodies (*Oölitic* or *Pea Iron-ore*). *Hæmatite*, already described as a mineral, appears as rock-like masses in beds, veins, and cavities (especially in limestones). Not infrequently it is found replacing limestone (see under ORE-FORMATIONS). As a rock it usually contains many impurities, such as clay, quartz, oxide of manganese, etc. It passes into ferruginous clay, etc. *Spathic Iron-ore* is a granular or compact aggregate of siderite, occurring in beds and as veins, especially among the older geological systems. *Clay-ironstone* is a variety of spathic iron-ore, containing much clay. It is brown to dark grey or black, and appears as thin beds and layers, or in the form of balls and nodules. It is a very common rock among the argillaceous strata of the Carboniferous system. In some cases it appears to have been deposited on the floors of ancient lakes, lagoons, and estuaries; in other cases it is of a concretionary nature —the ferruginous matter originally diffused through an argillaceous bed having become aggregated around fossils or other foreign bodies, so as to form nodules of various size. Many of these nodules are septarian (Plate XXIX. 1). *Blackband-ironstone* is simply a clay-ironstone containing a large proportion of carbonaceous matter (from 10 to 52 per cent.). Many marine clay-ironstones contain the iron-silicate, *chamosite*, in addition to the carbonate. Such rocks are usually greenish in colour and are often oölitic. The Cleveland Ironstone of the Middle Lias and the Northampton Ironstone of the Middle Jurassic are typical examples. (For occurrences of magnetic iron-ore, see under ORE-FORMATIONS.)

III. Organically derived Rocks

The more important rocks included in this division are largely composed of organic remains—plant or animal as the case may be. Some, however, are due, or partly due, rather to the action of living organisms. Amongst the latter are Flint and some kinds of Calcareous Tufa and Ironstone. The origin of flint has already been briefly considered (p. 73). Bog iron-ore not infrequently owes its origin to the action of bacteria, which are able to separate iron from water, and to deposit it about and within their substance as a hydrate. Water-loving plants are also largely concerned in the formation of calcareous tufa, which is not always due entirely to the mere evaporation of aqueous solutions. The carbonic acid which enables the water to hold the calcium-carbonate in solution is decomposed by bog-mosses and their allies, and a calcareous crust is thus gradually deposited upon the plants. Many thick masses of tufa have in this way resulted partly from chemical and partly from organic action. Considerable accumulations of siliceous sinter are likewise due in large

PLATE XXI

Microscopic Structure of Minerals and Rocks



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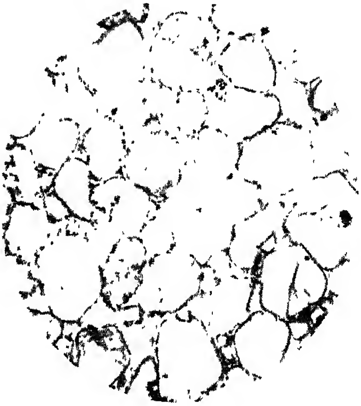

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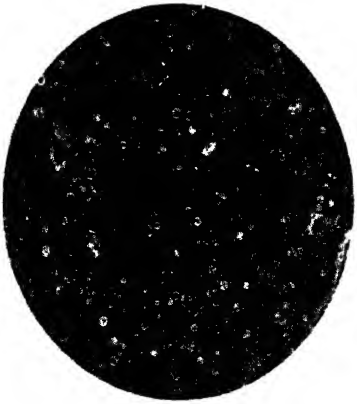

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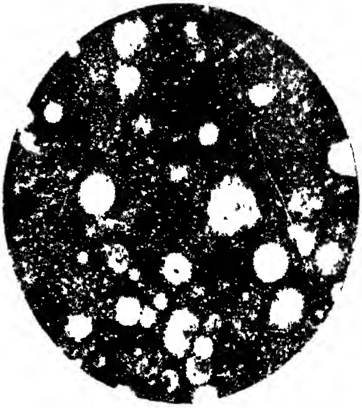


4.

1. Sandstone. Angular and subangular sand grains, mostly quartz, held together by a limonitic cement. × 35.
2. Aeolian sandstone, Penrith. Well-rounded sand grains, mostly quartz, coated with iron oxide and cemented together by crystalline quartz in optical continuity with the sand grains. × 20.
3. Chalk. Contains fragments of globigerina and other foraminifera, "chalk spheres," sponge-spicules, etc. along with finely-divided calcite of (?) organic origin. × 20.
4. Radiolarian chert, Portmore, Eddlestone, Peebles. A red jasper-like chert enclosing remains of radiolaria. × 35.

[*To face page* 75

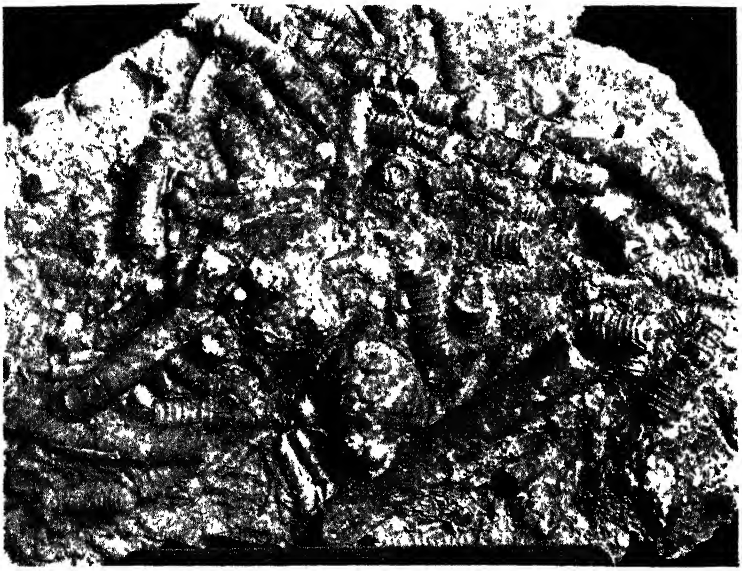
measure, as already indicated, to the vital action of minute algæ. But of still greater importance are the rocks which owe their formation to the action of humic acids derived from the decomposition of organic matter. These acids attack the iron-bearing mineral constituents of rocks, and form ferruginous solutions ; and when such solutions are exposed to the air they are oxidised, and hydrate of iron (bog iron-ore) is precipitated. There can also be little doubt that organic acids, derived from the decomposition of sponges and other forms of life, have had much to do with the formation of flint and chert, which might, therefore, be included among organically derived rocks as fitly as under chemically formed rocks. The most characteristic representatives of the former class are calcareous, siliceous, carbonaceous, bituminous, and phosphatic rocks, of which there are many varieties.

Limestone.—Of this rock there are innumerable kinds. All are composed essentially of carbonate of lime, but few do not also contain carbonate of magnesia. While some are very pure, others are crowded with impurities. They vary greatly also as regards texture—ranging from extremely fine-grained and compact rocks to coarse aggregates of shells and corals. Grey and greyish-blue limestones are very common, but many are green, purple, yellow, red, brown, black, or pure white. While these rocks differ as regards their hardness and specific gravity, the common and most characteristic types have usually a hardness of 3 or thereabout and a specific gravity of 2·6 to 2·8. One of the best-known limestones is common *Chalk*—a white fine-grained earthy rock, generally soft and meagre to the touch, soiling the fingers. It is sometimes composed largely of the shells of foraminifera, together with the débris of various forms of marine life—more or less reduced to the condition of a fine meal or flour (Plate XXI. 3). *Oölite* is similarly composed of organic débris, but is characterised by the oölitic structure already described as occurring in certain chemically formed calcareous deposits. In thin sections seen under the microscope the spherules show a concentric and radiated structure—the latter, however, being sometimes wanting. Similar spherules have been observed forming not only in mineral springs such as those of Carlsbad (*Sprudelstein*), but in shallow water in the Great Salt Lake of Utah, and on the coral beaches of the Bahamas. They may owe their origin to the deposition of calcareous matter on particles of sand which are kept in motion so as to become more or less equally encrusted, but in the formation of some modern oölites, as well as of certain oölitic limestones of earlier date, lime-secreting algæ have also played a part. *Shell-marl* is an earthy aggregate of shells (most frequently of freshwater origin), with a larger or smaller proportion of argillaceous matter. It often passes into *Lacustrine Limestone*, which is usually a fine-grained, dull white or grey rock—sometimes earthy, sometimes compact.

Limestones, which are composed conspicuously of the débris of crinoids, corals, or shells, as the more prominent ingredients of the rock, are known respectively as *Crinoidal*, *Coral*, and *Shelly* limestones (Plate XXII.). Occasionally, the organic structure of such rocks has been obscured or even entirely effaced by subsequent molecular changes—the mass becoming crystalline. Shelly limestones often acquire special names, according to the relative abundance of some particular shell, as *Nummulite-*, *Hippurite-*, *Ammonite-*, *Gryphæa-limestone*, etc. *Common Limestone* is usually grey or blue and fine grained to compact. In many common limestones the organic structure is only revealed in thin sections under the microscope. On the weathered faces of such rocks, however, fossil remains may often be readily detected.

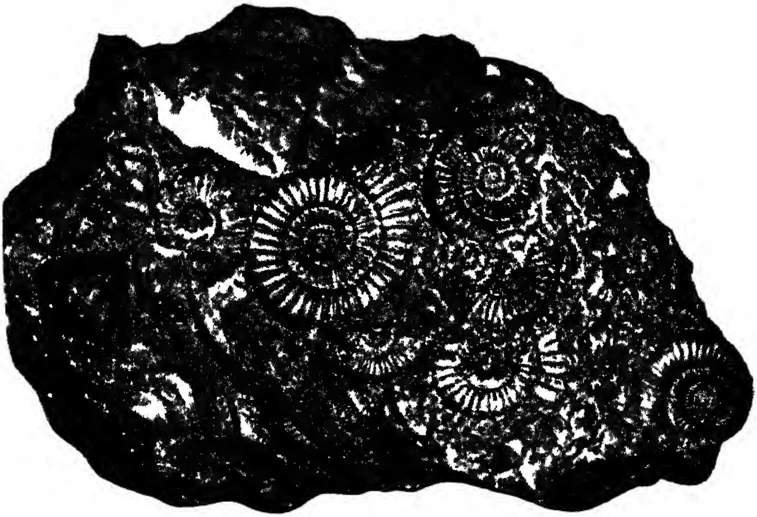
Siliceous Rocks.—Included here are deposits formed on the sea-floor or on the beds of lakes by the accumulation of the skeletal portions of radiolaria and diatoms and the spicules of sponges. Radiolaria are marine organisms which flourish chiefly in tropical seas and the remains of which constitute considerable proportions of the abyssal deposits known as *radiolarian oozes*. These oozes are known to cover extensive areas of the sea-floor in the Indian and the western Pacific Oceans. Radiolaria have been important rock-building organisms since pre-Cambrian times. Unconsolidated deposits are termed *Radiolarian Earths*; when consolidated they are commonly called *Radiolarian Chert* (Plate XXI. 4), or, if red in colour, *Radiolarian Jasper*. Some of these rocks are of abyssal, others of shallow-water origin. The radiolarian cherts, like the cherts of chemical origin, are very hard, compact rocks; sometimes they are laminated, but more often they exhibit little trace of bedding.

Diatoms, which are unicellular algæ, form an important



1. CRINOIDAL LIMESTONE. Nearly natural size.

Photo by T. C. Day.



2. SHELLY LIMESTONE. Nearly natural size.

[*To face page* 76

part of the plankton in the seas, particularly in the polar regions, and also in many fresh-water lakes. Their remains accumulate as extensive deposits of *diatomaceous ooze* in the deeper parts of Arctic and Antarctic Seas, and shallow-water diatomaceous deposits are found not infrequently in fresh-water lakes. Unconsolidated *Diatomaceous Earth* of fresh-water origin, known also by names such as *Infusorial Earth*, *Tripoli-powder* and *Kieselguhr*, is of common occurrence in this country in deposits laid down in late-glacial and post-glacial lakes. Similar deposits of Tertiary and Cretaceous age are known from many parts of the world. Diatomaceous earth is of considerable economic importance. It is used as an absorbent in the manufacture of high explosives ; it makes an effective polishing powder ; and it is also used in making light-weight silica-bricks and porous silica-ware, etc. Consolidated diatomaceous deposits are called *Diatomite*, or, if the cementing material is mainly siliceous, they are termed *Diatomaceous Chert*.

Marine oozes in which siliceous sponge spicules are the chief constituent are known from only a few localities. The consolidated equivalent of such deposits, *Sponge-chert*, has been described from a number of geological formations dating from the Lower Carboniferous onwards. The most noteworthy are those found in the Lower and Upper Greensands of the Cretaceous system. Nearly all the known sponge-cherts are of marine origin.

Carbonaceous Rocks.—The carbonaceous rocks, chief of which are the true coals, comprise those solid combustible substances which have been formed from the altered remains of once living vegetation, now preserved in the rocks of various geological systems. As all coals are derived, in the first instance, from a peat-like substance, we may consider first the formation of *peat*. In the northern hemisphere peat is widely distributed and may be classed as *upland peat* and *lowland peat*, but in each case is made up of the remains of plants adapted to conditions where water stands at or near the level of plant growth for the greater part of the year. It is usual, under these conditions, to find the living plants growing upon a sub-stratum of dead and altered plant material.

The processes involved in the change of plant tissues into peat may be described as bio-chemical and due mainly to the action of fungi and bacteria. By these agents the dead plant tissues are broken down in a definite order giving rise to secondary products, but, owing to the presence of water, decomposition is retarded and a residue remains, the nature of which depends partly on the original plant material and partly on the extent to which biochemical decay has been allowed to proceed. A modern peat may show layers of plant fragments, some recording the succession of plant life in the swamp or bog, others marked by the abundance of certain tissues such as leaves or spores, the whole mass being permeated by dark brown or black amorphous decomposition products. A bed of peat a few feet in thickness may represent a long period of time and contain within itself important evidence of climatic variations.

The change from peat to coal is brought about by processes which may be described as geo-physical and geo-chemical. These come into play when the peat is buried under other sediments, involving compression and rise in temperature. At the same time the rise in temperature leads to shrinkage, loss of water, and the progressive elimination from the peat of oxygen, hydrogen, and part of the carbon. These changes may be enhanced by the effect of earth movement and, locally, and frequently to a very marked extent, by igneous intrusions. All coals consist of carbon, oxygen, hydrogen, nitrogen, and sulphur along with a varying amount of mineral matter, and the coals which have been most modified by geo-physical and geo-chemical action have the highest content of carbon. As the original nature of the peat and the degree of subsequent alteration to which it has been subjected have varied widely, the resulting varieties of coal are numerous. The least altered coal is known as *lignite*; intermediate varieties have been given names such as *gas coal*, *household coal*, and *steam coal*, while the most altered is known as *anthracite*.

All true coals show well-marked bands to which special names have been given. Thin inconstant layers with obvious macroscopic plant fragments are known as *fusain*, dull layers with a finely-granular surface as *durain*, and clear bright bands of two kinds as *clarain* and *vitrain*. The physical and chemical characters of these bands are of great practical importance. Thus, the incombustible residue (ash) is relatively high and constant in the durain, high but variable in the fusain, and low in the clarain and vitrain. The chief coking elements of the coal are the clarain and the vitrain. The durain gives a poor brittle coke while the fusain does not coke. The fusain being friable yields most of the coal dust in mines and is thus a factor in the propagation of underground explosions.

Further, the fusain, with its highly porous structure and capacity for absorbing oxygen with rise of temperature, is believed to act as a fuse, igniting the clarain and vitrain leading to "spontaneous combustion" of the coal underground, in coal heaps on the surface, and on board ship. On this view the spontaneous combustion of coal, so fruitful of accident, is due to oxidation of the coal substance itself.

While a coal may be formed of plant-débris which has been drifted to the site where now found and therefore independent of the substratum on which it lies, most good coal seams rest upon an *underclay* crowded with rootlets representing the swamp soil on which the coal-forming plants grew.

In most great coal-fields a number of seams may occur at intervals through hundreds and even thousands of feet of strata which consist for the most part of sandstones and shales of various kinds, but may include ironstones and estuarine and even marine limestones. The coals themselves and the accompanying strata indicate that the conditions which prevailed during the formation of our major coal-fields included the following conditions:—(1) wide areas at or near sea-level or some inland water-level; (2) climatic conditions favourable to luxuriant plant growth; (3) slow progressive subsidence of the area which may have been accompanied by uplift in adjacent regions to supply the sedimentary material which entombed the successive swamp levels.

Bituminous Rocks.—Included often with the true coals, but probably best considered separately, are a number of coal-like and shale-like rocks known as **cannel** or **parrot coals.** The terms "cannel," a corruption of candle, and "parrot," allude to the long flame and crackling sound with which they burn. Typical cannel is dark brown or black in colour with a silky lustre and a well-marked conchoidal fracture. It does not show the characteristic banding of the true coals but, instead, an extremely fine lamination. The inorganic impurity is high as compared with ordinary coal, from which it is distinguished further by its high content of volatile matter, many cannels yielding, on distillation, forty to sixty gallons of crude oil to the ton.

A thin section of cannel when viewed under the microscope shows a translucent dark brown ground mass containing occasional small plant fragments, small reddish-brown oval bodies, probably resin, and, in varying amounts, thin layers and isolated groups of light yellow algal remains to which further reference will be made in the next section. Cannels seldom contain large fossils, but remains of ostracods are common, and the scales, teeth, and bones of fish are sometimes found. Their mode of occurrence is characteristic, since they usually form part of an ordinary coal-seam and are thin, lenticular in form, and of limited extent. In respect of their mode of occurrence and their characters it is considered that they represent material accumulated in lagoons and open pools in the coal swamps, and consist partly of the remains of algæ and other lowly aquatic plants, and partly of the débris of land plants blown or washed from the adjacent forests. The animal remains found in them support this view.

Under the name **torbanite** we may include certain special deposits found in various parts of the world but seldom in thick beds or of great lateral extent. They vary in colour from yellow to brown or black, have a dull lustre and show, especially when weathered, an extremely fine lamination. They are remarkable for their high yield of oil on distillation, amounting in some cases to 120-160 gallons to the ton. Thin sections viewed under the microscope show that the rock is made up mainly of ovoid "yellow bodies" in a dark brown matrix like that of a cannel coal. The true nature of these yellow bodies, which yield most of the oil, has given rise to much discussion, but the original suggestion of Edgeworth David, that they represent the remains of colonial gelatinous algæ, has been confirmed by the discovery in South Australia, East Africa and elsewhere of comparable deposits, made up chiefly of the remains of algæ identical with or closely allied to the modern *Botryococcus*.

Oil-Shales are finely-laminated rocks, dark brown or black in colour, tough, sectile, and giving a brown streak. In the field they are seen to be resistant to weathering, a feature which distinguishes them from ordinary carbonaceous shales. The bulk of the rock consists of fine argillaceous material impregnated with a dark brown or black amorphous substance —the "kerogen" or "pyrobitumen"—which yields oil on distillation. Near igneous intrusions natural distillation of the shale has led to the impregnation of the neighbouring sediments and even the eruptive rock itself by oil and viscous forms of bitumen. The exact nature of the original material which has given rise to the kerogen is not known, and may not have been the same in all cases, but is probably finely comminuted débris of land plants. The "yellow bodies" met with in torbanite also occur but in smaller amount. Other fossils found in the shales include tests of ostracods and remains of fishes. Sun-cracks and desiccation-breccias are common and, indeed, all the characters of oil-shales point to deposition in shallow, brackish, or salt water. Their nearest equivalents among present-day sediments are the black and grey muds forming in shallow water where the supply of oxygen is limited.

Crude **petroleum** or "rock oil," as it occurs in nature, is mainly a mixture of hydrocarbons belonging to the paraffin, benzene, and naphthene series. Some varieties are viscous solids, some are liquid and others are gaseous. While petroleum may occur locally—no doubt derived by natural distillation from coal and oil-shale—the great oil-fields of the world occur commonly in shallow water marine or estuarine sediments where coal or oil-shale may be absent. The exact nature of the original material which, by slow distillation, has given rise to the oil is a matter of dispute, but in most cases it has probably been derived from the residue of land plants. That which distinguishes petroleum from other sedimentary deposits is its power of migration from the rocks in which it was formed to "reservoir rocks" which, by reason of their open texture, afford storage room. Such rocks are sandstones and cellular limestones, and in these great stores of oil may accumulate. Where these rocks are covered and sealed by relatively impervious beds such as shales, the petroleum may accumulate under great pressure due to occluded gaseous fractions of the oil, to rock pressure, and to the buoyant effect of ground water. When the covering rocks are pierced by the drill the petroleum may rise to the surface. Channels of escape, such as joints, faults, or the oil-bearing stratum itself at its outcrop, may be impregnated with solid bitumen, representing the residue of the petroleum from which the lighter fractions have evaporated.

Phosphatic Rocks—Phosphatic deposits, derived originally from the apatite (calcium phosphate) so widely distributed in eruptive rocks, are formed chiefly by the action of animals. By weathering on a land surface the calcium phosphate is slowly released to the soil, passing to plants, and so to animals, in whose bones it is returned to the earth. In this way, where there is an abundant vertebrate fauna, the uppermost layer of the soil becomes richer in phosphorus than the deeper layers; on wide areas where animal life is scarce the reverse is found to be true.

Part of the land-derived calcium phosphate, which finds its way in solution to the sea, is utilised by lowly forms of animal and plant life which serve as food to higher forms. Fish are eaten by sea-birds which resort to safe islands for nesting, and in such sites as the rainless islands off the western coast of South America valuable deposits of *guano* have been formed, made up of the excrement of the sea-birds along with the remains of fish and other material carried ashore by them. More usually the guano is leached by rain, and the soluble calcium phosphate, ammonium phosphate, and free phosphoric acid are carried underground and modify the underlying rocks. Where these consist of lavas, phosphates of iron and aluminium may be formed, but, where the island has a capping of coral rock, calcium phosphate may be formed on a large scale by replacement of the limestone, and may occur where no trace of guano now exists and the birds have long abandoned the site. Valuable deposits of phosphatised coral-rock formed in this way are found on Christmas Island, south of Java, and on Ocean Island in the Gilbert Archipelago.

Phosphatic rocks may form also in shallow warm seas with abundant life through the phosphatisation, usually in the form of layers of nodules, of the bones, shells, etc., on the sea-floor. Deposits of this kind in course of formation have been detected in the Gulf of Mexico and in the Florida Strait, and rocks formed similarly, but of an earlier date, occur in Florida and elsewhere. On the sea-floor the nodules may be concentrated on surfaces of contemporaneous erosion, through wave and current action, and later further concentration may be affected through the solution of the enclosing limestone by ground water or by the sorting action of running water in streams and river channels. Chalk and other limestones commonly contain a small proportion of phosphates as in the Upper Chalk of Tatlow, Buckinghamshire, and in the Pliocene beds of Suffolk.

CHAPTER V

ROCKS—*continued*

Metamorphic Rocks, their General Characters. *A*. Schistose and Foliated Rocks. Mica-schist. Schistose Grits. Chlorite-schist. Talc-schist. Hornblende-schist. Gneiss. *B*. Granoblastic Rocks. Quartzite. Granulite. Marble. Hornfels. *C*. Cataclastic Rocks, their General Characters. Mylonites, Friction-breccias.

III. METAMORPHIC ROCKS

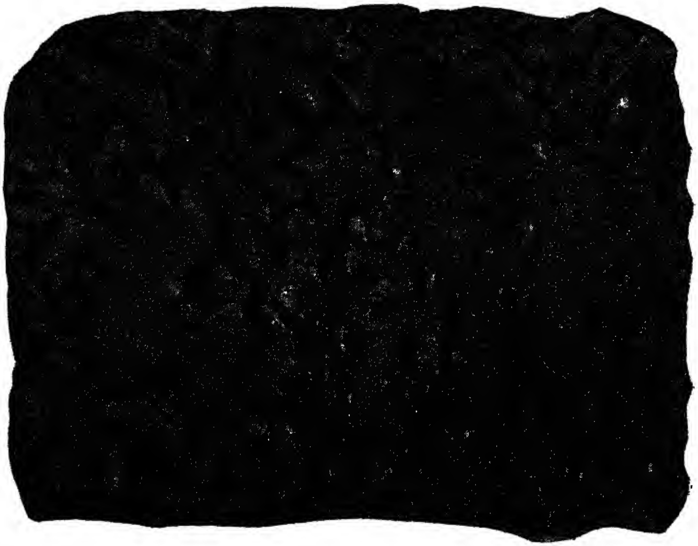
THE rocks of this great class are for the most part crystalline and characterised by the structures known as schistosity and foliation. The term " foliated " is often applied to all metamorphic rocks in which there is a more or less parallel disposition of the minerals, coarsely-foliated rocks being designated gneisses (Plate XXV. 1), and those in which the parallelism is well developed and closely spaced being termed schists (Plate XXV. 2). Some workers, however, prefer to call the latter rocks *schistose* and to restrict the use of the term *foliated* to rocks in which particular minerals are segregated in greater or less degree into lenticles or streaks or bands which are often sharply contrasted with adjacent bands. Schists tend to split or cleave readily into slabs parallel to the schistosity. In foliated rocks, on the other hand, individual folia thicken-and thin-out rapidly, and alternate irregularly ; the several folia are not as a rule readily separated from each other—the minerals of one layer being usually more or less closely intermingled, felted, and welded with those of adjacent layers. Schistosity and foliation are structures which differ markedly from the lamination and bedding of sedimentary derivative rocks. They are in most cases easily distinguished also from the fluxion or fluidal structures often present in crystalline igneous rocks, but it should be noted that plutonic masses sometimes exhibit, particularly in their marginal parts, a kind of fluxion-foliation which is original and not the result of metamorphism.

Metamorphic rocks, however, differ much in texture and structure. Although the majority of crystalline metamorphic rocks are schistose or foliated there are many which show only faint traces, and others which, though markedly crystalline, are quite devoid of such structures. Of common occurrence, for example, are types which have a *granoblastic* structure, the rocks consisting of a mosaic of dominantly equidimensional crystals (Plate XXV. 3). In other cases metamorphism may bring about a marked structural change such as the production of *slaty-cleavage* (see p. 225), while the original clastic constituents of the rock are only in part recrystallised. Or, again, rocks subjected to intense compression have sometimes been crushed into fragments, or even finely pulverised, without acquiring a crystalline structure. Such rocks are said to be *cataclastic*.

There can be no doubt that many crystalline schists and gneisses originally existed as mechanical sediments, and that their present constitution is the result of subsequent changes. This is proved by the simple fact that all gradations can be traced from unaltered sedimentary rocks into rocks which become more and more markedly crystalline and foliated as they are followed in some particular direction. Again, rocks, such as schistose conglomerates and schistose grits, which still retain obvious evidence of their clastic origin, are not infrequently met with intercalated between beds of mica-schist —an arrangement at least suggestive of the original sedimentary character of the latter, which can be readily confirmed by study of their chemical composition. Further, the occasional occurrence of fossils in crystalline schists leaves no room to doubt that such schists are simply more or less metamorphosed sedimentary rocks.

In other cases it can be proved just as readily that certain schistose and foliated rocks were originally of igneous origin. Again and again we encounter massive igneous rocks, such as granite, dolerite, etc., passing by insensible gradations into foliated or schistose rocks. Occasionally, as already noted, primary fluxion-foliation may be developed during the period of cooling and crystallisation of an igneous mass, but in the great majority of such cases we are compelled to conclude that the schistosity and foliation are superinduced. Some metamorphic rocks, however, are of composite origin, consisting of an intimate admixture of intruded igneous material and

PLATE XXIII



1. Spotted Slate. Nearly natural size.

2. Gneiss. About two-thirds natural size.

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intensely metamorphosed sediments. (For a fuller discussion of metamorphism, see p. 218.)

Using structural and textural characters as a basis for classification we may recognise three main divisions of metamorphic rocks, namely, A. SCHISTOSE AND FOLIATED ROCKS, B. GRANOBLASTIC ROCKS, and C. CATACLASTIC ROCKS.

A. SCHISTOSE AND FOLIATED ROCKS

Here are included the **Schists** characterised by their relatively fine-grained texture and their well-marked schistosity, and the **Gneisses** with their characteristic coarse grain and distinctive foliation. Varieties of schist are usually distinguished by prefixing the names of the dominant constituent minerals.

Mica-schist is composed essentially of micas and quartz, the schistosity being due mainly to the parallel orientation of the flaky micas. White mica (muscovite) and black mica (biotite) are both of common occurrence, either alone or together. The quartz may be granular or lenticular. Accessory minerals occur in great variety; sometimes, as in the case of garnet, staurolite, etc., they are much larger in size than the other constituents of the rock and the resulting structure is known as *porphyroblastic*. The character of the mica is indicated in names like *biotite-schist*, *muscovite-schist*, and *sericite-schist*. When the accessory minerals are abundant their presence is denoted by designations such as *chlorite-muscovite-schist*, *garnet-biotite-schist*, *staurolite-mica-schist*, *graphite-mica-schist*, etc. When graphite largely takes the place of micas the rock is known as *graphite-schist*.

Mica-schists have been formed mainly by the metamorphism of argillaceous sediments, the metamorphism being of a moderately high grade. Sometimes, however, sericite- and muscovite-schists represent metamorphosed acid igneous rocks. **Clay-slate,** which results from a low-grade metamorphism of argillaceous sediments, is a finely-granular to compact clay-rock. It can be split readily into thin plates along planes which may coincide with the original planes of deposition, but more usually cross these at various, often high angles. The colour of the rock may be blue, green, grey, purple, brown, or red. Slate is composed mainly of argillaceous matter, but many other ingredients may be present, such as quartz, feldspars, micas, chlorites, carbonaceous matter, rutile, iron-oxides, pyrites, etc. Some of these minerals are original constituents of the shale, but much of the mineral matter has been recrystallised as minute scaly micas, chlorites, etc., in planes at right angles to the maximum pressure which brought about the metamorphism of the shale into slate. It is this orientation, together with the similar orientation brought about by the rotation of pre-existing flaky minerals, that determines the characteristic cleavage.

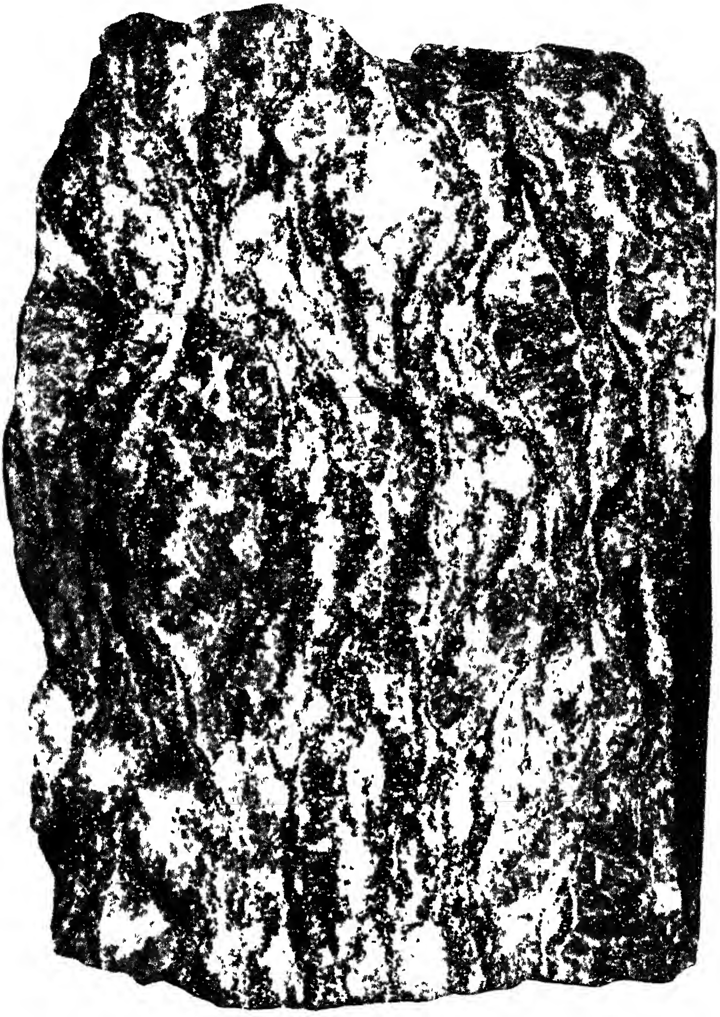
Knotted- or *Spotted-slate* contains spots or concretionary knots (Plate XXIII. 1), which in some cases represent aggregations of graphitic matter, in others incipient and ill-developed crystals of chiastolite or of cordierite, the new minerals and graphitic knots having resulted from superinduced contact metamorphism. When crystals of chiastolite or of cordierite are well developed the rocks are known as *chiastolite-slate* and *cordierite-slate*. Spotted-slates and cordierite-slates, etc., may be little altered otherwise, or they may contain much new mica, and so gradually pass into cordierite-mica-schist, etc. *Phyllite* is more crystalline than clay-slate. It is a schistose rock, the cleavage-planes of which are lustrous with small white micas and frequently wrinkled. It may be regarded as a passage-rock between clay-slate and mica-schist.

Schistose Grits represent incipient stages in the metamorphism of coarse arenaceous sediments. The clastic character of the larger grains of quartz, feldspars, and micas is still recognisable, but they have assumed a parallel arrangement which gives a rude schistosity. The interstitial sericitic and chloritic material has recrystallised and often has taken on a schistose character.

Chlorite-schist is a schistose aggregate of scaly green chlorite, usually with quartz, and often accompanied by such minerals as sericite, carbonates, albite, epidote, and magnetite. The magnetite sometimes occurs as conspicuous porphyroblasts. Most chlorite-schists have been formed by the metamorphism of basic and ultrabasic igneous rocks such as basalts, basaltic tuffs, dolerites, gabbros, and peridotites. Some, however, distinguished by the highly-aluminous character of their chlorite, were originally impure argillaceous or calcareous sediments.

Talc-schist is a green to greenish-grey or yellow schistose rock, very soft, and with a pronounced unctuous or soapy feel. It consists chiefly of scaly talc, with which quartz, chlorite, or mica are often associated. Other minerals which may be present include tremolite, antigorite, magnesite, siderite, and magnetite. The carbonates occur occasionally as large rhombohedral crystals. Talc-schists are metamorphosed ultrabasic igneous rocks.

PLATE XXIV



Coarse Gneiss, showing Lenticular "Eyes" or Phacoids. Nearly natural size.

[*To face page* 87

Hornblende-schist is a schistose rock with dominant hornblende (Plate XXV. 2). Other minerals often present are albite, oligoclase, andesine, quartz, epidote, zoisite, biotite, chlorite, and garnet. The hornblende is occasionally porphyroblastic in habit. Where the amphibole is an actinolitic variety the rocks are known as *actinolite-schists.* Some hornblende-schists are metamorphosed basic igneous rocks; others were originally calcareous sediments. *Tremolite-schists,* whose chief constituent is tremolite, have also originated in two ways—from the metamorphism either of ultrabasic igneous rocks or of siliceous dolomitic limestones. Massive hornblende-rich types, in which the structure tends to be granoblastic rather than schistose, are termed *amphibolites.*

Gneiss.—Here are included all coarsely-crystalline foliated metamorphic rocks (see Plates XXIII. 2, XXIV., and XXV. 1). Banded and lenticular structures are characteristic, the concentration of particular minerals being due partly to differences in the distribution of material in the original rocks, partly to the segregation of like materials during the metamorphic processes. More or less granoblastic lenticles and bands may alternate with bands which are in greater or less degree schistose. Although the one may grade into the other, typical gneisses are readily distinguished from typical schists by their coarser crystallinity and by the absence of persistent close-set planes of schistosity. Most gneisses are feldspathic and quartzose, but those minerals are not essential. Other common constituents include micas, amphiboles, pyroxenes, garnet, cordierite, sillimanite, magnetite, etc.

Gneisses of sedimentary origin have been called *paragneisses,* those of igneous origin *orthogneisses.* The terms *psephitic gneiss, psammitic gneiss* and *pelitic gneiss* are used to designate gneisses derived respectively from gravel-, sand-, and clay-rocks. In the naming of specific varieties of these rocks it is customary to prefix the name of some abundant or significant constituent mineral. Common types are *biotite-gneiss, hornblende-gneiss, pyroxene-gneiss, cordierite-gneiss, sillimanite-gneiss,* etc.

B. GRANOBLASTIC ROCKS

Under this heading are grouped metamorphic rocks which consist essentially of a crystalline mosaic of more or less equidimensional constituents, and in which schistose and foliated structures are completely absent or very poorly developed (Plate XXV. 3, 4).

Quartzite.—A pure metamorphic quartzite consists of a mosaic of quartz crystals. In such a rock, which may have been derived either from a pure quartz sandstone or grit or from a chert, all traces of the former clastic nature of the rock have been obliterated. In many quartzites a considerable proportion of recrystallised feldspar enters into the composition of the mosaic. Where argillaceous, calcareous, or ferruginous impurities have been present in the original sediment their former presence is indicated by the occurrence in small amount of new minerals whose character depends on the nature of the impurities and on the grade of the metamorphism. Thus quartzites often contain scattered crystals of new chlorite, biotite, epidote, augite, etc. The name "quartzite," it should be noted, is also applied to non-metamorphic sandstones and grits in which the clastic grains, mainly quartz, are cemented by infiltrated crystalline silica.

Granulite.—When sandstones are highly feldspathic they may give rise to metamorphic rocks known as granulites. These consist chiefly of a granoblastic aggregate of quartz and feldspars, in which the latter minerals are present in large amount. The feldspars include orthoclase, microcline, and acid plagioclases. Throughout the mosaic of quartz and feldspar there occur usually scattered flakes of biotite and muscovite. Garnets, epidotes, cyanite, and other new minerals may also appear. Common accessories are magnetite, apatite, sphene, zircon, etc., and these minerals, which for the most part represent original minor constituents of the sandstones, are often concentrated in bands as in the original sediments. Sometimes the micas of the granulites tend to have a parallel arrangement. Granulites of the above type are widely distributed in the Moine-schist Series of the Scottish Highlands. They have a flaggy character which is determined by the fact that the granoblastic bands are separated by thin micaceous seams, which represent doubtless the intercalation of argillaceous and chloritic layers in the sandstones. Granulites with similar composition and texture may also result from the metamorphism of acid igneous rocks. Varietal names such as *biotite-granulite*, *garnet-granulite*, *cyanite-granulite*, etc., indicate the presence of some significant mineral accompanying the quartz and feldspars.

Other granulites, darker in colour and heavier, and known as *pyroxene-granulites*, consist of a mosaic of hypersthene, augite, labradorite, magnetite and, often, garnet. They are in most cases metamorphosed basic igneous rocks (Plate XXV. 3).

Marble.—Granoblastic structure is also characteristically developed in marble, which, if derived from a pure limestone, consists of a mosaic of equidimensional grains of recrystallised calcite, all traces of clastic and organic structures having been obliterated. When the original limestones have contained siliceous, aluminous, magnesian and ferruginous impurities the marbles produced in their metamorphism contain silicates such as wollastonite, grossularite, vesuvianite, zoisite, epidote, diopside, tremolite, anorthite, etc. The resulting rocks are termed *wollastonite-marble*, *diopside-marble*, etc.

Dolomite, when the pressure is sufficiently high, may simply recrystallise to form *dolomite-marble*, which is generally finer-grained than ordinary marble. More frequently, however, the metamorphism of dolomite gives rise to de-dolomitisation. The magnesian part of the dolomite separates as small octahedral crystals of periclase (MgO) while the $CaCO_3$ recrystallises as a mosaic of calcite. The resulting rock is known as *periclase-marble*. Very often the periclase, which is readily hydrated, is pseudomorphed by brucite $\{Mg(OH)_2\}$ and the rock becomes a *brucite-marble*. Examples of these rocks are *pencatite*, a fine-grained brucite-marble derived from pure dolomite, and *predazzite*, which was originally a dolomitic limestone and therefore contains a larger proportion of calcite. Another good illustration of de-dolomitisation is seen in the formation of *forsterite-marble*. Here the original dolomite has contained silica as an impurity, and the magnesia has united with the silica to form the magnesia-olivine, forsterite. The rocks consist of well-formed crystals of forsterite embedded in a matrix of calcite or of calcite and dolomite. Frequently the forsterite has been altered to serpentine, and then the serpentinous marble is known as *ophicalcite*.

Hornfels.—Hornfels is the name given to tough, very fine-textured granoblastic rocks produced by contact metamorphism. When the chief minerals have a flaky or columnar habit they are arranged characteristically in criss-cross fashion. Typically hornfelses are so compact as to assume a flinty or horny aspect, but sometimes they appear finely-crystalline to the naked eye. Some, such as *andalusite-hornfels* (Plate XXV. 4), and *cordierite-hornfels*, are metamorphosed argillaceous rocks; some, known as *calc-silicate-hornfelses* were originally impure limestones or dolomites; others, again, are reconstructed igneous rocks. Hornfelses usually occur in immediate contact with intrusive igneous masses.

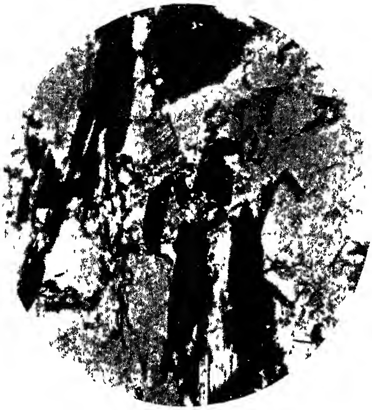
C. CATACLASTIC ROCKS

The origin of metamorphic rocks will be considered in Chapter XV. Here it is only necessary to point out that many of these rocks have acquired their present structure and texture under the influence of the intense strains and stresses to which the crust of the earth has been subjected. Under enormous pressure the constituent minerals of certain rocks have been rendered in a sense plastic and compelled to flow. Such rocks have consequently acquired a "shear-structure" not unlike the fluxion-structure developed in lavas. Rocks of this kind are schistose and usually holocrystalline. In other cases, however, a rock subjected to intense compression has been merely crushed into fragments or even pulverised, without acquiring a thoroughly crystalline character. No hard-and-fast line separates these two kinds of structure. In point of fact, one often passes by insensible gradations into the other. Typical examples of the former are crystalline and schistose; while similar examples of the latter are fragmental or *cataclastic*. But such cataclastic rocks often exhibit a "streaky" or even schistose character, and their constituents may to some extent show a superinduced crystalline, or rarely glassy texture. In many cases, however, they consist of a compacted aggregate of smaller and larger angular and subangular fragments, forming finer or coarser brecciated masses, which are neither crystalline nor schistose. Rocks of this type are often well developed along one or both sides of faults or dislocations of the crust (see Chapter XI.).

Mylonites.—This is the name given to very fine-grained cataclastic rocks. They are typically developed along the lines of great overthrusts or reversed faults, and are usually closely associated with crystalline schistose rocks, into which indeed they often pass. Most frequently they show well-developed "shear-structure"—the rock being composed mostly of minute fragments and particles with now and again larger

PLATE XXV

MICROSCOPIC STRUCTURE OF MINERALS AND ROCKS



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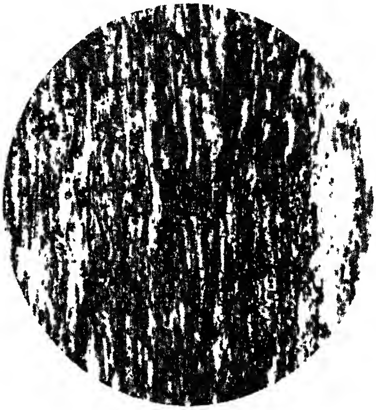

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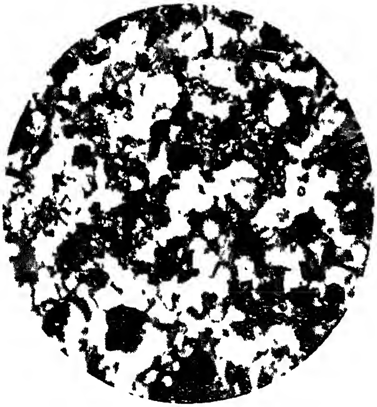

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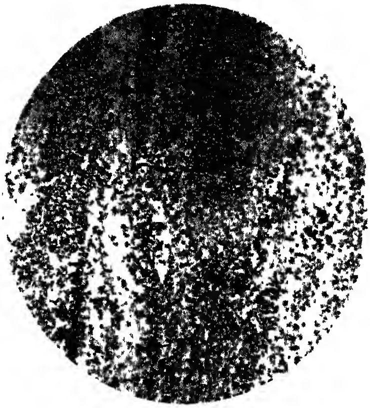

4.

1. Muscovite-biotite-gneiss, Sgurr nan Clach Geala, Ross-shire. Coarsely-crystalline, foliated. × 20.
2. Hornblende-schist, Loch na Craige, Aberfeldy. Finely-crystalline; schistose. × 20.
3. Hypersthene-granulite, Saxony Coarsely-crystalline; granoblastic. × 20.
4. Andalusite-hornfels, Andlau, Vosges. Finely-crystalline; granoblastic. × 20.

[*To face page* 90

fragments, set in a streaky groundmass of crushed materials. When the nature of the larger fragments (of minerals or rock) is obvious, not infrequently one is able to say what the original uncrushed rock may have been. *Flinty Crush-rock* is a black flinty-looking material found in association with mylonites and representing a fritted or sometimes fused variety of the latter. Usually it is amorphous, but occasionally it shows subsequent incipient crystallisation in the form of the development of microlites and spherulites.

Friction- or Crush-breccia.—This is an aggregate of angular and subangular fragments, varying in size up to one foot or even more in diameter. Breccias of this kind occur in the same way as mylonites, into which they often pass. All gradations, indeed, may be traced from coarse breccia into mylonites, and from the latter into schists. When there has been considerable movement of the rock-débris and the fragments have been rolled over and more or less rounded, the rock is termed a **friction-conglomerate.** Although friction-breccias are best developed in regions where the rocks have been subject to much compression—to folding and great dislocations and displacements—and where frequently metamorphism is more or less pronounced, they are nevertheless not confined to such regions. Faults traversing strata of all kinds are not infrequently accompanied by breccias. Sometimes these are confined to a line of fracture, filling up the space between the two walls of a fault; while in other cases the rocks forming one or both walls of a fault have been jumbled, shattered, and brecciated. The stones in such **fault-breccias,** as they are termed, are not infrequently rubbed smooth and striated on one or more sides.

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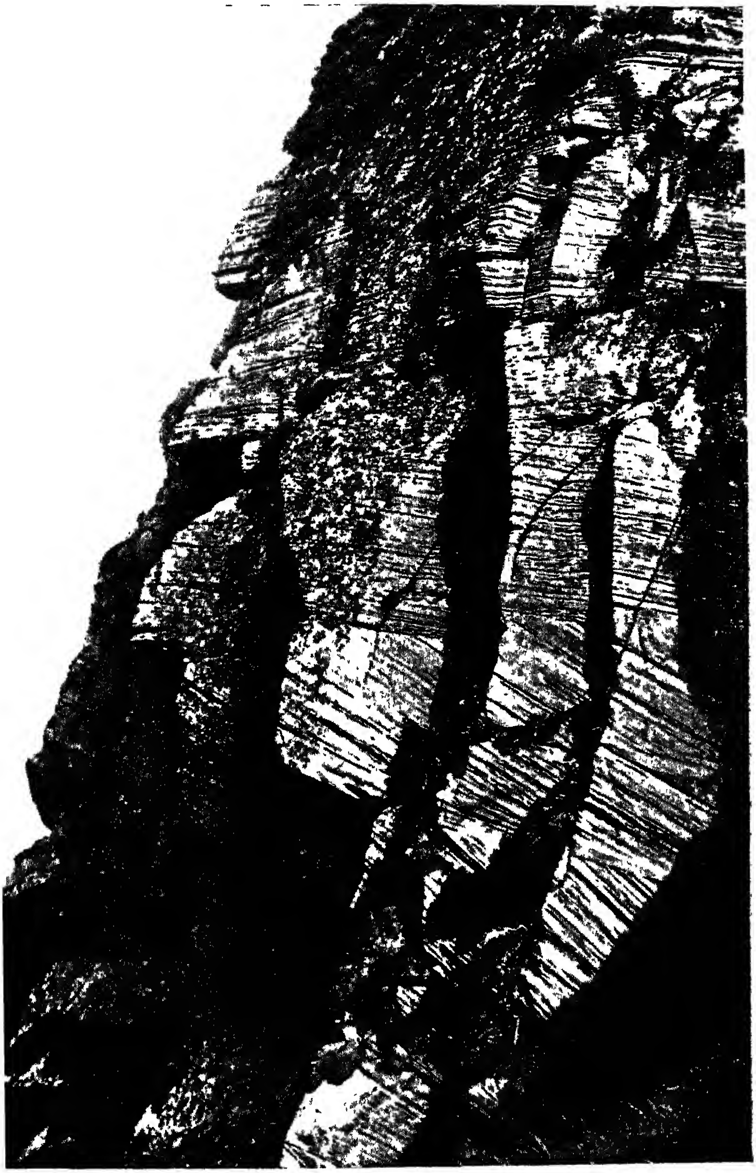
CHAPTER VI

FOSSILS

Modes of Preservation of Organic Remains. Kinds of Rock in which Fossils occur. Fossils chiefly of Marine Origin. Importance of Fossils in Geological Investigations. Climatic and Geographical Conditions and Terrestrial Movements deduced from Fossils. Geological Chronology and Fossils.

HITHERTO we have been concerned with rocks mainly as aggregates of mineral matter, and only a passing reference has been made to the fact that certain derivative accumulations contain *fossils*—the remains and traces of formerly living creatures. We have seen, it is true, that some kinds of rock, such as coal and limestone, consist chiefly of the débris of plants and animals, but we have now to realise that almost every variety of derivative rock may be more or less fossiliferous, and that traces of former life have been met with, now and again, even in certain igneous and metamorphic rocks.

When a plant or animal, or any portion of either, is buried in sediment, it becomes subject to decomposition. This process usually results in the destruction of all organic compounds of carbon and nitrogen, and even the harder and more durable parts undergo some change, and may eventually become disintegrated and entirely disappear. Certain chemical changes, however, may supervene before the process of destruction is completed. In many cases, for example, carbonisation takes place—various gases are given off, and the organic tissues are gradually transformed into carbon. Or mineral matter may be introduced in solution so as to fill up all the cavities of the original structures, or even to replace completely the substance of the organism. Fossils, therefore, are met with in all states of preservation. Exceptionally, the entire organism has been preserved with little or practically no change of the original substance—the bodies having been protected from decomposition by the nature of the materials in which they have been entombed. As examples may be cited



CURRENT BEDDING IN SANDSTONE, MAOL DONN, ARRAN.

From H.M. Geological Survey's Memoir, "The Geology of North Arran," etc.

the carcasses of the extinct mammoth and woolly rhinoceros which, long ages ago, were sealed up in the frozen earths and ice of Northern Siberia, so that when in recent times they became exposed, owing to the gradual dissolution of the medium in which they had been buried, their bodies were in so fresh a state that dogs devoured the flesh. Insects, spiders, and plants have similarly been completely preserved in amber (fossil gum or resin); but, in most cases, these would appear to be more or less carbonised. The more common methods of preservation, however, are as follows :—

Incrustation.—The organism under certain conditions is enveloped in a covering of mineral matter. Calcareous tufa, for example, is often precipitated upon plants growing near springs containing much calcium-carbonate. In the case of thermal waters siliceous sinter may be the incrusting substance. Vegetable and insect remains preserved in this manner are often more or less carbonised, or they may be entirely decomposed and dissipated, leaving merely hollow moulds behind them.

Carbonisation.—Plant-remains and chitinous animal structures, without having been previously incrusted, frequently undergo carbonisation—a deoxidising process which takes place under conditions permitting of only a limited access of air. Thus plants accumulated in marshy ground, or on the floor of lake or estuary, or buried in mud, etc., tend to undergo a kind of distillation whereby the oxygen and other gases are gradually eliminated—the carbon in this way becoming concentrated.

Moulds and **Casts.**—The substance of a buried organic body may be entirely dissipated, and only a mould of it remain. Should this mould be subsequently filled with mineral matter, a cast showing the external form of the original will be produced. This is a common kind of fossilisation. Many fossil shells, for example, are simply casts, and do not contain a particle of the original substance. When an empty bivalve or univalve shell is enclosed in a deposit, the sediment usually at the same time fills the vacuity. Afterwards, the shell itself may be gradually dissolved and removed by percolating water. The cavity thus formed may be subsequently reoccupied by mineral matter, and in this way a perfect cast will be produced. Not infrequently, however, the space left by the shell remains unfilled, containing in its centre the stony kernel which formerly occupied the interior of the original. Should this kernel not adhere to the matrix it will rattle, like a nut in its shell, when the specimen containing the fossil is shaken.

Permeation and Molecular Replacement.—Mineral matter has often thoroughly permeated an organic body, and filled up all its pores and cavities—a process which has usually been preceded, accompanied, or followed by carbonisation. Not infrequently, under these conditions, the original substance itself is more or less molecularly replaced by mineral matter, with partial or perfect preservation of the internal structure. This kind of fossilisation is well illustrated by some specimens of silicified wood, the minutest structures of which have been so completely replaced that a slice of the specimen, viewed under the microscope, reveals as much as a section of the original wood itself could have shown. Permeation and molecular replacement may be exemplified by one and the same fossil, so that the two kinds of fossilisation are frequently hard to distinguish. An organic body which is permeated and molecularly replaced by mineral matter is a true petrifaction.

In cases of true petrifaction, the replacing mineral is usually either silica (mainly chalcedony or opal) or calcium carbonate. The same substances also play the most important part in the formation of incrustations and casts, which is just what might have been expected when we remember how very widely calcareous and siliceous solutions are diffused. Other substances, however, not infrequently replace organic remains, such as the compounds of iron (pyrite, marcasite, hæmatite, limonite, and siderite), and, less frequently, gypsum, barytes, fluor-spar, and various metals and metallic compounds.

It is not only the relics and remains of plants and animals which are termed fossils, but any recognisable trace of their former existence—any impressions or tokens left behind them—whether it be footprints, tracks or trails, burrowings, castings, or coprolites, or even the markings traced on sediment by the waving to-and-fro of sea-weeds, etc.—are all equally fossils.

Kinds of Rock in which Fossils occur. As a rule, the best preserved fossils are met with in the finer grained sedimentary rocks, as in marls, limestones, clay and shale, and fine argillaceous or calcareous sandstones.

Calcareous Rocks. Argillaceous limestones and marly shales are often highly fossiliferous, and the fossils are usually well preserved. But pure limestones, which have become more or less crystalline, frequently appear to be poor in organic remains, so that when a fresh fracture of the rock is obtained, few or no traces of any structure may be visible. On surfaces which have been for some time exposed to the weather, however, fossils not infrequently project in bold relief—the limy matrix in which they are embedded offering less resistance to atmospheric action. The same phenomena characterise many dolomitic limestones.

Argillaceous Shales.—Not infrequently these are rich in fossils—their impervious character having doubtless tended to the preservation of the remains. Some shales, however, are very barren, or the few fossils present may be included in nodular concretions of calcium-carbonate, siderite, or other substance.

Sandstones are not so frequently fossiliferous as shales, for which there are at least two reasons. First, a sandy sea-floor, owing to frequent or constant movement of the sediment, is not favourable to sedentary forms of life, and is therefore avoided by organisms which cannot shift for themselves. An ordinary siliceous sandstone might therefore be expected to be somewhat barren. Second, the permeable character of sandstones must favour the subsequent passage of percolating water which so frequently dissolves and removes organic bodies. Massive thick-bedded quartzose sandstones and red sandstones are, as a rule, singularly poor in organic remains. Certain thin-bedded argillaceous and thick-bedded calcareous sandstones, however, are not infrequently highly fossiliferous —and this is especially the case when the sandstones occur in beds alternating and interosculating with dark carbonaceous or lighter coloured calcareous shales.

Conglomerates are generally unfossilferous, or, if fossils are present, these are usually more or less rolled and water-worn. For example, we may obtain, in some Carboniferous and Jurassic conglomerates, worn fragments of the trunks and branches of trees—but the more delicate twigs and leaves are absent. So, again, in gravels and conglomerates of Pleistocene and Recent age, only the more resistant large bones and teeth of mammals are ever met with, and they are often rolled and broken. There are exceptions to every rule, however, for now and again tolerably well-preserved shells do occur in conglomerates.

Volcanic Tuffs. In certain bedded volcanic tuffs fossils occur, but this is not common. Plant-remains have been encountered even in the coarse tuffs and agglomerates that occupy the throats or necks of certain ancient Carboniferous volcanoes in Scotland. Probably these represent trees, etc., which grew upon the slopes of the old cones after the volcanoes had become extinct. More rarely still, charred fragments of trees have been met with enclosed in the lower portion of an ancient lava.

Schistose Rocks. It need hardly be said that these rocks are usually destitute of organic remains. Nevertheless, fossils are occasionally present in schists, as in certain metamorphic Ordovician and Silurian rocks in Southern Norway, and in the crystalline schists of Mesozoic age which enter into the structure of the Central Alps.

Fossils differ much not only in regard to the state of preservation of their internal structure, but also of their external form. In many cases they have been much compressed—what were formerly cylindrical branches, for example, have often been flattened, so as to give lenticular sections when cut across. In limestones, marly shales, and calcareous sandstones, shells, corals, etc., usually retain their original shapes; while in argillaceous shales, fossils of all kinds are apt to be more or less flattened—a rule, however, which has many exceptions. In clay-slates and rocks which have obviously been subjected to much compression, fossils are usually highly distorted and often recognised with difficulty.

By far the great majority of fossils are of marine origin, most of the sedimentary formations in which they occur having been deposited upon the floor of the sea. Fresh-water and terrestrial accumulations form an inconsiderable proportion of the series of stratified rocks, so that relics of the occupants of former rivers, lakes, and dry lands are of relatively infrequent occurrence. At the present day aquatic animals largely exceed terrestrial animals in number, and the same was the case in earlier ages. On the other hand, in the world of to-day plants are mostly terrestrial forms, and although we know very little of the land-plants of the earlier geological periods, there is no reason to doubt that terrestrial floras have, for unnumbered ages, greatly surpassed marine floras in abundance and variety. The conditions for the accumulation and preservation of plants in the still waters of lakes, lagoons, and estuaries are upon the whole more favourable than those that obtain upon the sea-floor. Further, many sea-weeds, with their loose, cellular tissues, are readily decomposed, while the great majority of land-plants with their vascular tissues are more enduring. For these and other reasons terrestrial plants frequently occur in abundance and in a better state of preservation than seaweeds.

It is obvious, therefore, that from a general point of view, marine organic remains are of most importance to the student of historical geology. It is unquestionable that the records of past times are preserved chiefly in the marine formations of the earth's crust. It is by studying these records that we are able to follow the main lines along which the world's development has taken place. The histories revealed by freshwater and terrestrial accumulations are, as it were, only episodes, although these episodes are usually most interesting and instructive. Now and again, indeed, they may be said to constitute more or less complete chapters of the general world-history. They tell us of the life of the land, of which only sparse traces are met with in marine formations. It is obvious, indeed, that the great majority of land-plants and animals must necessarily disappear without leaving any trace behind. The surface on which they live is pre-eminently a region of disintegration and denudation rather than accumulation. It is, therefore, only under exceptional circumstances that relics of land-life can be preserved. The sea, on the other hand, is *par excellence* the region of accumulation. The creatures which live and die there are thus much more likely to be represented. It is simply for this reason that the records of marine life are so much more continuous and abundant than those of land-life. Hence relics of land-plants and animals are, generally speaking, of relatively less value to the geologist for the purpose of comparing and correlating separate areas of fossiliferous strata. Nevertheless, some of the most absorbingly interesting and fascinating chapters in the world's history have been rescued from terrestrial and lacustrine formations. It must also be noted that in certain cases it has been possible to correlate widely separated areas of terrestrial and freshwater deposits by means of their fossils. This holds specially true for certain systems and stages, as in the case of the Coal-Measures, the coals and lignites of later age, and the estuarine and freshwater deposits of Secondary, Tertiary, and more recent times.

A glance at the several great phyla of the animal kingdom will serve to show the relative importance to geologists of marine organic remains.

Protozoa.—Among those lowly organised forms are many which possess calcareous or siliceous hard parts. Members of this phylum therefore occur in great abundance in marine formations of all ages.

Porifera (Sponges).—A few of the living types are of freshwater habitat, but the great majority are marine, and the same was the case in earlier ages. As many sponges are furnished with a calcareous or a siliceous skeleton or framework, they are somewhat common fossils in many marine deposits.

Cœlenterata.—These also are essentially marine. The phylum includes the corals, which are among the most abundant fossils—often forming immense sheets and masses of limestone.

Echinodermata.—This is another great division of marine creatures, among which are star-fishes, sea-urchins, and stone lilies—the calcareous tests and skeletal remains of which are among the most frequently occurring fossils in many formations.

Annelida (Worms).—These are known as fossils chiefly by their tracks and castings—being for the most part soft-bodied creatures, they have rarely been preserved. As these tracks and castings occur chiefly in marine sedimentary rocks it is very doubtful if any of them indicate earthworms. The "tubes" formed by many marine annelids are often met with as fossils.

Molluscoidea.—These are among the commonest and most abundant fossils. One great division (Polyzoa) comprises the lace-corals and sea-mats, which are chiefly marine, and, as fossils, often occur associated with other marine organisms. The other great division (Brachiopoda) is exclusively marine, and includes the lamp-shells, etc.—one of the most important types of life with which the student of historical geology has to deal.

Mollusca.—The same holds true with the marine mollusca, which are more or less abundantly represented in every great system of strata. Not only are they of prime importance by reason of their abundance as regards genera, species, and individuals, but their shells, like those of the brachiopods, appear often in a comparatively perfect state of preservation. Freshwater shells and land-snails are of much less frequent occurrence as fossils.

Arthropoda.—This phylum embraces lobsters, crabs, scorpions, spiders, centipedes, and insects, and is of great value to the geologist—the crustaceans more especially, for, a large proportion of these being marine, they are well represented by fossils. Some of the extinct types, as Trilobites, for example, are very characteristic fossils of the older systems in which they occur. Freshwater and terrestrial forms are not so commonly encountered, since they are largely confined to freshwater deposits and to lignite- and coal-bearing strata.

Vertebrata.—This great phylum is most numerously represented by marine fishes. Marine types of reptiles and mammals also occur now and again, but with the exception of the fishes vertebrate remains of any kind are sparingly met with. Remains of birds and land-mammals are almost confined, as might have been expected, to freshwater and terrestrial accumulations.

Importance of Fossils in Geological Investigations.—It need hardly be said that the study of fossils to the biologist is of surpassing importance. Such study, indeed, cannot be ignored by him if he would understand the life-history of existing types. But it is not with that side of palæontological enquiry that the practical or field-geologist is mainly concerned. He values fossils chiefly for the help they yield him in his endeavours to realise the conditions under which sedimentary rocks were formed, and to ascertain the chronological sequence of the strata.

Climatic Conditions deduced from Fossils.—Individual fossils, if of existing species, and occurring *in situ*, may give valuable evidence as to former climatic conditions. Two examples may be cited. Certain relatively recent accumulations of calcareous tufa, occurring at La Celle near Paris, have yielded numerous remains of the Canary laurel (*Laurus Canariensis*). There is no doubt, therefore, that this plant formerly flourished in Northern France. It is no longer a native of that country, however, its headquarters being in the Canary Islands, where it is found flourishing luxuriantly in the woody regions with a northern exposure, between a height of 1600 feet and 4800 feet above the sea—regions which are nearly always enveloped in steaming vapours and exposed to the heavy rains of winter. The temperature there keeps above 69° F. during the greater part of the year, rarely falling in the winter months below 59° or 60°, and only on the coldest days reaching 49°. The presence, therefore, of this variety of laurel in the Pleistocene tufa of La Celle shows that the winter climate of Northern France must formerly have been very mild. The laurel in question is most susceptible to cold and, as it flowers in the winter season, it is obvious that repeated frosts, such as are now experienced in the north of France, would prevent it reproducing its kind. Another and more familiar example of the important evidence which is sometimes afforded by fossil remains of existing types is that of the Polar willow (*Salix polaris*)—a characteristic arctic plant living in Northern Lapland, Spitsbergen, etc. This dwarf willow has been met with again and again in Pleistocene deposits in Southern Sweden, Denmark, England, etc., and in various parts of Central Europe, as far south as Bavaria and the low-lying parts of Switzerland. It cannot be doubted, therefore, that the appearance of the Polar willow so far south of its present habitat, points to a very considerable climatic change—arctic conditions would seem to have prevailed at a relatively recent period in what are now the temperate latitudes of our continent.

It is obvious, however, that the evidence of fossils as to climatic conditions must be much stronger when a whole assemblage of organic remains tells the same tale. In the case of the tufa of La Celle, for example, the Canary laurel is accompanied by the remains of many other plants, as well as by shells of land-snails, each of which is indicative of a milder and more equable climate than now characterises Northern France. And the same is the case with the Polar willow, the evidence supplied by it being fortified by that of other high northern plants, and by the relics of such animals as lemming, arctic fox, etc.

Great caution must be exercised in deducing climatic conditions from the occurrence of extinct forms of life. For these, even when they very closely resemble living types, need not have existed under similar conditions. For example, so long as the mammoth and woolly rhinoceros were only known from their skeletal remains, they were generally supposed to have existed under the same climatic conditions as their living representatives. We know now, however, that each was provided with a thick woolly and hairy covering, and was capable, therefore, of withstanding the rigours of a northern winter.

In dealing with fossils consisting largely of extinct species, it is the general facies of a flora and fauna, and not individual forms, that are to be specially considered. For example, the London Clay (Eocene) has yielded a large number of types having a tropical or subtropical aspect. Amongst the plants are forms of sarsaparilla, aloe, amomum, fan-palms, fig, liquidambar, magnolia, eucalyptus, cinnamon, various proteaceous plants, etc.; while the animals include turtles, tortoises, crocodiles, tapir-like pachyderms, and certain birds with affinities to living tropical types. Associated with these are many forms of molluscan life which have their nearest living representatives in warm latitudes, such as cones, cowries, volutes, nautilus, etc., together with sword-fish, saw-fish, sharks, and rays. All this is good evidence that a warm climate prevailed during the deposition of the London Clay. The land was clothed with a tropical or subtropical vegetation, while corresponding types of animal-life haunted the rivers and flourished in the sea of the period.

In the older geological systems we may say that all the species and nearly all the genera are extinct, so that any general resemblance which an assemblage of Palæozoic fossils may have to those of some particular groups of living plants and animals may have no climatic significance whatsoever. We may feel sure, indeed, that the abundant flora of the Carboniferous period could not have flourished under arctic or even cold temperate conditions of climate; and we may be equally convinced that the abundant corals and cephalopods of Palæozoic times, with their numerous congeners, were not denizens of cold seas. Existing conditions might even lead us to believe that the massive limestones of those early ages were most likely formed in genial waters. For at the present day it is in warm seas that lime-secreting organisms such as corals, pelagic molluscs, and foraminifera flourish most abundantly, and are there giving rise to widespread and thick accumulations of calcareous matter. But it would be rash to conclude that the climatic conditions of Palæozoic times were similar to those of our present warm latitudes.

When the geographical distribution of Palæozoic floras and faunas, however, is kept in view, we may advance our inferences a step further. Should the fossils or groups of fossils of some particular formation be known to occur over vast areas of the earth's surface, in arctic, temperate, subtropical, and tropical latitudes, and even in similar latitudes of the Southern Hemisphere, we should be justified in the inference that the climatic conditions indicated by the fossils in question must have been singularly equable. The mere fact that in the earlier stages of the world's history cosmopolitan forms of plant- and animal-life abounded, affords good ground for believing that the climatic conditions of those far past times differed considerably from the present. The climate of the globe in those days could not have been differentiated into such distinct zones as is now the case.

Geographical Conditions deduced from Fossils.—Fossils naturally yield evidence as to terrestrial, freshwater, and marine conditions.

(a) *Land-surfaces*. These are seldom preserved. Nevertheless they do occur in strata belonging to widely separated periods. Now and again, for example, the stools and roots of trees penetrating ancient soils occur interbedded with sedimentary strata, a good example being furnished by the "dirt-bed" of Portland. This dirt-bed is simply an old soil containing the roots and stumps of extinct forms of cycads and conifers. It is intercalated between beds of freshwater origin, a succession which shows that, after the deposition of a wide area of fluviatile mud, dry land prevailed and eventually became covered with forests. Subsequently, owing probably to subsidence, the forest was submerged and buried under newer accumulations of fluviatile mud and silt. Many of the coal-seams of the Carboniferous period, with their underclays, tell a similar tale, and the same history is repeated by not a few of the lignites belonging to later geological periods. [Certain coals and lignites, however, appear to represent masses of vegetable matter which have probably been drifted from the land into estuaries and shallow bays of the sea.] The not infrequent occurrence of arachnids, insects, lizards, and land-snails, associated with beds of coal and lignite, is additional evidence of terrestrial conditions. Amber, again, is an abundant product of the lignite-bearing beds of Germany, and unquestionably represents the gum and resin which exuded from some of the forest trees of Tertiary times.

(b) *Lacustrine conditions.* These are indicated by the presence of numerous freshwater molluscs and small crustaceans which are sometimes so abundant as to form beds of marl and limestone. Plant-remains, insects, and other relics of land-life, such as reptiles or mammals, often occur in lacustrine deposits. It is from lacustrine and estuarine deposits, indeed, that we obtain our fullest information as to the life of former land-surfaces.

(c) *Marine conditions.* Relatively deep or, at least, clear water is indicated by thick masses of limestone, more or less abundantly charged with corals, sea-lilies, and other marine organisms. This inference is based partly on the fact that these limestones are comparatively pure—that is, they contain relatively little insoluble matter, and this is usually in a very finely divided state. In short, it is evident that such limestones have accumulated over parts of the sea-floor not reached by ordinary sediment—conditions which, as a rule, can obtain only at a considerable distance from the shore, and often, therefore, in somewhat deep water. Further, we judge from the analogy of the present, that, as existing corals only flourish in clear water, their predecessors probably demanded similar conditions. This inference is strengthened by the fact that when, towards the top of a bed of limestone, the rock becomes more and more impure, the corals, and certain of their congeners, often begin to diminish in size, and even to become somewhat distorted, as if the influx of muddy sediment had acted prejudicially upon their growth and development.

Shallow-water conditions and proximity of the land are often evidenced by trails, burrows, and castings of annelids, tracks of crustaceans, etc., footprints of reptiles, amphibians, birds, or mammals. Along with these the strata may yield more or less well-preserved plants, insect-remains, and other relics of land-life. Beds containing such fossils are not infrequently estuarine deposits and often exhibit ripple-marks, rain-prints, and sun-cracks.

Terrestrial Movements deduced from Fossils. — The presence of marine fossils in a rock obviously indicates oscillations of the sea-level. The appearance, for example, in our maritime districts, at various heights above the present sea-level, of terraces of sand and gravel, crowded with sea-shells of still living species, is proof positive of some recent crustal movement—either the land has risen or the sea-floor has subsided. Again, the existence at various depths on the sea-bottom of peat overlying the stools of trees belonging to kinds that still flourish in these islands, is evidence sufficient of a recent subsidence of the land.

Geological Chronology and Fossils.—In many cases it is quite impossible to correlate the formations occurring in separate regions by means of lithological characters alone. Within limited areas these may be reliable, but strata begin to change in character as they extend in various directions. Limestones, for example, may become gradually more and more argillaceous until at last they merge into shales, while these last may in their turn eventually pass into or interosculate with sandstones. Now, unless such changes could be followed in continuous open section, we could not possibly be sure that certain given beds of limestone, shale, and sandstone were exactly contemporaneous—all laid down on one and the same sea-floor. These rocks are so dissimilar that, unless we actually traced the connecting passages, we could not tell how one was related to another. So far as lithological character is concerned, they might each have been formed at a different time. But if the separate sections of strata contained fossils having the same general facies—and especially if several species were common to the limestones, the shales, and the sandstones, we could no longer doubt that all these rocks were accumulations formed in one and the same sea. Fossils are thus of paramount importance in the correlation of strata.

In the attempt to determine the relative age of our fossiliferous strata, the most important step was taken when William Smith, the father of Stratigraphical Geology, determined the sequence of the Mesozoic strata of England, and ascertained that each subdivision of that great series of rocks was characterised by the presence of certain particular types of fossils. Following his lead, geologists have since established the stratigraphical succession of fossiliferous strata throughout the major portion of the world. It is now recognised that every well-defined formation is marked by the presence of a particular flora or fauna, or by certain genera and species which are restricted to it. The presence of these *type-fossils*, as they are termed, enables the geologist at once to assign the rocks in which they occur to some definite horizon or stage in the great succession of sedimentary accumulations.

It is obvious, therefore, that some knowledge of type-fossils must be of great use in Practical Geology. How greatly they help a geologist in his endeavour to work out a stratigraphical succession will be shown when the subject of geological surveying comes to be discussed.

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CHAPTER VII

STRATIFICATION AND THE FORMATION OF ROCK-BEDS

Consolidation of Incoherent Accumulations. Lamination and Stratification. Extent and Termination of Beds. Contemporaneous Erosion. Diagonal Lamination and Stratification. Grouping of Strata. Contemporaneity of Strongly Contrasted Strata. Surface-markings.

TECTONIC or Structural Geology treats of the arrangement of rocks, or the mode of their occurrence. It deals, in short, with the architecture of the earth's crust. The study of rocks, Petrology, is concerned simply with the nature and origin of rocks as aggregates of mineral matter. For the purposes of geology, however, this is not sufficient—rocks must be studied not only in hand specimens but as constituents of the earth's crust. The geologist must take note of the positions they occupy as rock-masses, and the relation which the various rock-masses bear to one another. It is only by such observations that the order of succession, or, in other words, the relative age of rock-masses can be ascertained, and the particular conditions under which they were formed, and the various changes they have since undergone, can be determined. It is, therefore, hardly too much to say that our knowledge of the many revolutions which have affected the earth's surface—the ever-changing geographical conditions of the past—is largely based on the study of structural geology.

In discussing the important subject to which the following chapters are devoted, attention must be largely confined to a description of rock-structures; but it may be helpful to the student now and again to consider what such structures mean, and to show how they may be interpreted by reference to existing operations of nature.

The structural geology of derivative rocks is upon the whole simpler and more readily understood than that of eruptive and metamorphic rocks, and therefore we shall consider first the phenomena which are specially characteristic of aqueous or sedimentary deposits. As we shall learn in the sequel, however, many of the structures presently to be described are met with likewise among igneous, and some of them even among metamorphic rocks.

Consolidation of Incoherent Accumulations.—By way of introduction to the present subject, a few remarks on the consolidation of rocks may not be out of place. Rocks, as we have learned, are not all equally compacted, and their state of solidification is no certain test of their relative age. It holds generally true, however, that the fragmental accumulations of early geological ages are more consolidated than those which have been formed in later times. We cannot doubt that conglomerates, sandstones, shales, limestones, tuffs, and volcanic agglomerates were formerly as loose and incoherent as any similar masses now in course of formation. There is one obvious way in which some of these accumulations have become hardened, and we can see the process in operation at the present day. Water percolating through loose sand and gravel introduces mineral matter which, as the water evaporates, is deposited between the grains and pebbles, and thus binds these together. Frequently a sediment becomes compacted by the chemical action of water upon its own constituents. Calcareous accumulations, for example, tend to become consolidated by the solution of the calcium-carbonate, and its subsequent precipitation in pores and interstices; what were formerly yielding incoherent masses become in this way converted into hard rocks, such as calcareous sandstones, grits, and limestones. We know also that loose or soft materials may be compacted by the weight of overlying masses. Peat, for example, taken from the bottom of a bog, some twenty or thirty feet in depth, is often so compacted that when dried it resembles lignite. In like manner thick artificial accumulations of loose rock-rubbish, as everyone knows, become in time sufficiently consolidated to serve as foundations for buildings. When we are assured, therefore, that many rocks of sedimentary origin, now visible at the surface, were formerly overlaid by hundreds or even thousands of feet of younger strata which have since been removed by the gradual process of denudation, we cannot doubt that the mere weight of such enormous masses must have tended to consolidate the beds upon which they rested. Once more, we note that heat tends to solidify deposits, as may be seen in the case of strata which have been baked and hardened by intrusions of formerly molten matter—eruptive masses. More potent and widespread, however, must have been the action of the internal heat of the globe upon thick accumulations of sediment deposited during long-continued subsidence of the sea-floor. Certain consecutive series of strata attain a thickness of 15,000 or 20,000 feet and more. It is obvious, therefore, that while the upper members of such series were being accumulated, the lower members must have been more or less affected by the rise of the isogeotherms or lines of equal subterranean temperature. According to what is known of the increment of heat downwards, a very high temperature must obtain at depths of 15,000 or 20,000 feet from the surface—certainly much in excess of the boiling-point of water. Strata brought in this way under the influence of the internal heat of the globe could hardly escape some degree of change. Not only would they be compressed by the superincumbent masses but if interstitial water were present, chemical reactions amongst the various rock-constituents might often be greatly stimulated—water acting as a more powerful agent under increased heat and pressure. It can hardly be doubted that such must have been among the chief causes of the consolidation of ancient sedimentary accumulations.

Pressure may be brought about, however, by other means than the mere weight of overlying masses. The earth is a cooling body, and as the crust sinks down upon the slowly contracting nucleus, it necessarily becomes subject to enormous lateral compression. To this it can only yield by folding and crumpling up, and thus the rocks of which it is composed are frequently more or less highly disturbed. Strata which originally occupied approximately horizontal positions are now flexed, bent, and inclined at all angles, and such highly disturbed rocks, no matter what their geological age may be, are invariably much compacted and sometimes so altered as to become truly crystalline and schistose. On the other hand, strata which have not been disturbed, but still retain their original horizontal position, are usually much less hardened, and rarely show any trace of metamorphism. The older Palæozoic rocks of this country, for example, are usually highly flexed and folded, and not only much compressed and hardened, but frequently rendered crystalline and schistose. In Central Russia, on the other hand, strata of the same age have retained their original horizontal position, and are so unaltered in general aspect as to resemble the sedimentary accumulations of much later times. The contrast between the undisturbed and more or less incoherent Eocene deposits of the London Basin and their much flexed and folded representatives in the Alps of Switzerland, is not less striking. Many similar contrasts might be cited, but it is enough to emphasise the fact that great crustal deformation is invariably accompanied by the induration of the rocks affected, no matter what their age may be. We may conclude, therefore, that the pressure induced by crustal movements has been one of the most effectual and widely acting causes of rock-consolidation.

Lamination and Stratification.—The most abundant and widely distributed rocks of derivative origin are undoubtedly the sedimentary types, conglomerate, sandstone, and shale. They have been spread out by the sorting action of water, and consequently occur in sheet-like form. Coarse gravel (*conglomerate*) has obviously been deposited upon beaches, or in shallow water at the mouths of rapid torrents, streams, and rivers. It may therefore be fluviatile, lacustrine, estuarine, or marine. In like manner sand (*sandstone*) and argillaceous sediments (*clay*, *shale*, etc.) are of both marine and freshwater origin. Sometimes a sedimentary rock has been deposited more or less rapidly; at other times the process of sedimentation has been gradual and protracted. In the latter case, this is shown by the structure of the sheet-like deposit, which is usually composed of successive layers or very thin laminæ. In a deposit more rapidly accumulated, this structure is either inconspicuous or wanting.

Lamination is typically represented by the finer grained sediments, such as argillaceous shales. The laminæ of such deposits vary in thickness from an inch or so down to the finest films, not thicker than ordinary writing-paper (see Fig. 4). As a rule they cohere only slightly, so that a rock of the kind is more or less readily separated along the planes of lamination. Not infrequently, however, the laminæ have, owing to pressure, become more adherent. The laminated structure being the result of successive depositions of fine sediment by periodical river-floods, or by tidal or other marine currents, usually indicates accumulation in quiet water. These conditions are met with in lakes and estuaries, and over such areas of the sea-floor as are not much disturbed by currents—that is to say, in relatively deep water. Although lamination is very characteristic of argillaceous rocks, it is by no means confined to these. Laminated sandstones are of common occurrence, particularly when the rock is very fine-grained and more or less argillaceous. In coarser grained sandstones the individual laminæ are thicker than in argillaceous shales. When they exceed an inch or so, however, they are often described as *layers*.

Bed or *Stratum* is the term applied to any sheet-like mass which has a more or less definite petrographical character, and is separated by well-marked parallel division-planes from overlying and underlying rocks. A bed may be homogeneous and without any apparent arrangement of its constituents, or it may consist of successive layers of laminæ. It is well to point out, however, that the terms "bed" or "stratum" and "layer" are purely relative. A sandstone consisting of a series of layers, for example, is often described as a *thin-bedded* rock. Again, a thin sheet of limestone, ironstone, or coal, intercalated in a series of shales, might be termed either a bed, a layer, or a seam.

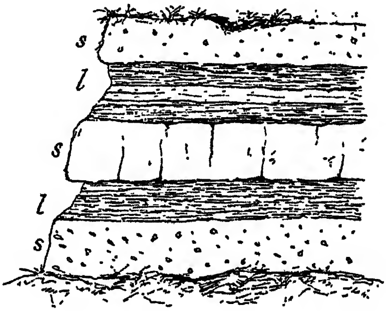


FIG. 4.—STRATIFICATION AND LAMINATION.
s, s, s, non-laminated beds; *l, l*, laminated beds.

The time required for the formation of any given thickness of sedimentary materials is necessarily indeterminate. Generally speaking, however, a bed of conglomerate may have been amassed more rapidly than an equal thickness of sandstone, and a sheet of sandstone may have been deposited in a shorter time than one of shale of equivalent extent and thickness. It is clear, however, that the rate of deposition of any particular kind of sediment must vary indefinitely. Certain sandstones, for example, may have been formed more rapidly than others of precisely the same character. Usually, however, where the rate of accumulation has varied in any marked degree, some evidence of this will be visible in the structure of the rocks. Thus, we may reasonably infer that a homogeneous sandstone, such as freestone or liver-rock, has been formed in less time than an equal mass of laminated sandstone. The liver-rock indicates continuous sedimentation, while the laminated sandstone points to a process of intermittent sedimentation. So, again, a structureless clay or loam has probably been accumulated more continuously, and therefore more rapidly, than a well-laminated shale. Nevertheless, it must be admitted that, in comparing separate beds of similar character and thickness, we can never be sure that an equal time was required for their deposition. Nay, even in the case of beds having the same composition and structure, and differing only in thickness, it cannot always be assumed that the thickest beds took the longest time for their accumulation. Probably, in most cases, they did, but many facts conspire to show that mere thickness is no sure test of the relative age of individual beds. If this be true of strata having the same character throughout, it is certainly not less true of beds which differ in composition and structure. A series of limestones and shales, one hundred feet in thickness, for example, may well have required for its formation a far longer time than a succession of several thousand feet of sandstones.

Intervals indicated by Planes of Lamination and Stratification.—The parallel division-planes separating individual strata are always more pronounced than planes of lamination, *i.e.*, the planes separating individual layers or laminæ. This naturally suggests that a longer time has elapsed between the accumulation of successive strata than between the deposition of successive laminæ or layers. The length of interval represented by planes of stratification, however, is indeterminate. It may be quite short or very prolonged. In the case of shallow-water sediments, which are apt to show rapid alternations of coarser and finer-grained deposits, no long intervals need have separated the deposition of the several kinds of sediment from each other. Rapid alternations of sediment are quite characteristic of alluvial, estuarine, and littoral or shore-accumulations. On the other hand, sediments accumulated in deeper water seldom show such rapid changes of character. They are usually fine-grained and persistent over wide areas. It is justifiable, therefore, to infer that planes of stratification amongst such accumulations will represent longer intervals than in the case of estuarine and littoral deposits. Should a pure marine limestone of some thickness, for example, be immediately underlaid and overlaid by thick argillaceous shales, as in the accompanying illustration (Fig. 5), we should be justified in assuming that the planes of stratification indicated lengthy intervals of time. Such an alternation of deposits would necessarily imply certain geographical changes, and these, as a rule, are only developed very slowly. We should infer that some change of conditions had arrested the deposition of muddy sediment represented by the lower beds of shale (sh^1)—either the source of supply was cut off, or the current which brought the sediment had lost its force, or was diverted in some other direction. The presence of thick, pure limestone (*l*), consisting of the débris of corals and other marine organisms, points to a long-continued period during which the water remained clear. Then the sudden appearance

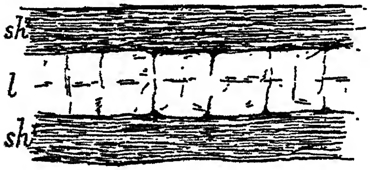


FIG. 5.—SHALES AND LIMESTONE.
sh^1, sh^2, shales ; *l*, limestone.

of the overlying shales indicates a resumption of the conditions which obtained during the deposition of the lower shales. Possibly the alternation of beds may point to crustal movements. It may be that the floor of the sea subsided so as to carry it beyond the reach of mud-transporting currents, and after a prolonged period of rest, during which the corals and their congeners flourished, a new crustal movement in the opposite direction brought the same region again within the influence of currents laden with fine sediment. Explain the alternation of strata as we may, it is obvious that the planes of stratification in this case indicate more or less prolonged intervals. Geologists do not doubt that in some cases these planes may well represent a longer period of time than was required for the accumulation of the various strata which they separate.

Extent and Termination of Beds.—Fine-grained deposits usually have a wider extension than coarse-grained accumulations. This is quite in keeping with what we know of the distribution of sediments in the lakes and seas of our own day. When a river enters a lake or estuary, the force of the current is immediately checked, and the heavier and coarser materials, gravels, etc., are at once thrown down. Grit and sand are swept out to a greater distance and more extensively distributed, while the finest particles travel further still and are spread over a yet wider area. Practically the same kind of sifting-out of sediments is effected by waves and tidal currents along an open coast-line. Banks of shingle and gravel accumulate close inshore, while grit and sand are carried further off, and the lightest or most readily transported sediment further still, the finer deposits invariably extending over the widest tract of sea-floor. Beds of shale, therefore, will generally have a greater lateral extension than beds of sandstone, grit, and conglomerate occurring in the same series of strata. Marine limestones, even when thin, often range over a very wide area. For their formation somewhat clear water is required and, unless they be of the nature of coral-reefs, they will usually have accumulated at some distance from any land and consequently often in relatively deep water. Under such conditions, therefore, we might have expected them to have a wide extension. All this is in keeping with the broad fact that accumulation of sediments proceeds with least interruption over those parts of the sea-floor which are not strongly swept by currents. Where there is much stir in the waters deposition of sediment is frequently interrupted, the sediments are coarse-grained, and show constant alternations of gravel, grit, and coarse sand. Where the sea-floor is not so liable to the scouring action of tidal currents, finer sand is spread far and wide and passes out, as greater depths are reached, into mud and silt, which extend over still wider tracts of undisturbed sea-floor. At last a zone is approached, beyond which little or no terrigenous material is carried. Here the most important oceanic accumulations are of organic origin—calcareous and siliceous oozes (see Fig. 6).

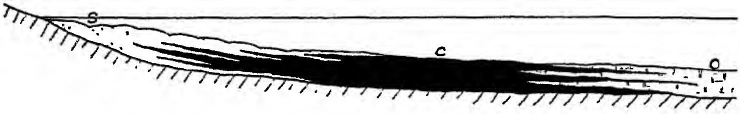


FIG. 6.—DISTRIBUTION OF MARINE ACCUMULATIONS.
s, gravel and sand ; *c*, clay, mud, etc. ; *o*, organic accumulations.

Each particular stratum in a sedimentary series may be looked upon as a lenticular sheet which, seen in section, begins at zero, thickens out regularly or irregularly as the case may be, until it reaches its maximum development, and then thins off in the same way. This lenticular structure can often be seen in one and the same quarry, where the whole group of beds may consist of a series of short, imbricating, overlapping, and interosculating lenticular sheets. Thicker and more continuous strata of sedimentary origin behave in precisely the same way, the beds of coarsest materials thickening out and thinning off more rapidly than the fine-grained deposits. Such being the manner in which strata are arranged, it is obvious that sections taken across the same series of strata at different places will not often show the same number of beds, or if all be present, they will probably vary in thickness. In the following section (Fig. 7), for example, we have from *a* to *d* an apparently consecutive series of beds, and there is nothing at that end of the section to show that the several separating planes of stratification do not represent similar intervals. Yet we see that one plane (*x*, *x*) really indicates a longer interruption or pause in the process of sedimentation than the others, a pause of sufficient duration to permit of the accumulation of the beds bracketed at *z*.

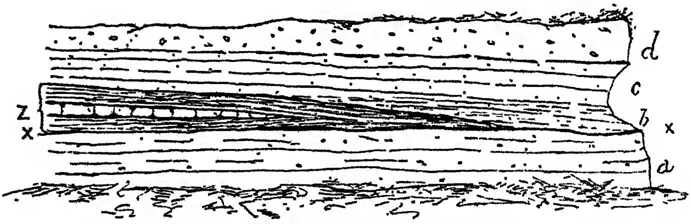


FIG. 7.—THINNING-OUT OF STRATA.

Contemporaneous Erosion.—The accumulation of relatively shallow-water deposits rarely goes on without interruption, for the currents which transport and lay down sediment not infrequently vary this action by scouring it out again and retransporting it elsewhere. Thus, during the formation of lacustrine, estuarine, and littoral and sublittoral deposits, accumulation and erosion often alternate. In the accompanying section (see Fig. 8) we have a series of beds, the accumulation of which has obviously been arrested at intervals. The bottom stratum, consisting of sandy clay (*c*), points to deposition in relatively quiet water. After such conditions had obtained for some time, the accumulation of fine sediment suddenly ceased, and the area of deposition was traversed by a stronger current which trenched and furrowed the stratum of sandy clay. As the force of this current declined, sand (*s*) began to be distributed over the denuded surface of the clay and eventually attained a considerable thickness. Eventually, however, the speed of the current once more increased, sedimentation was again locally arrested, and the process of erosion repeated, the sand being in its turn trenched and furrowed, and subsequently covered by arenaceous clay (c^1) just as this latter became denuded and afterwards overlaid by grit and sand (s^1).

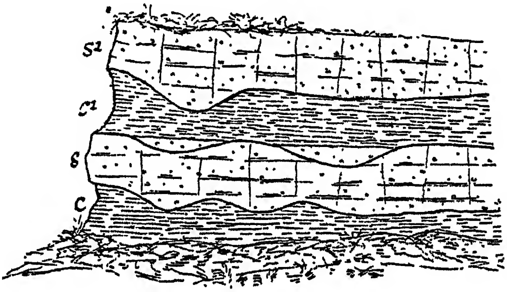


FIG. 8.—CONTEMPORANEOUS EROSION.
c, c^1, sandy clay; s, s^1, sandstone, grit, etc.

Diagonal (*Oblique or Cross-*) *Lamination and Stratification.* While it is generally true that sedimentary deposits are spread out in approximately horizontal sheets, now and again both laminæ and bedding show much irregularity—not only the individual beds, but the layers of which they are composed, are often inclined to each other at various angles. This irregularity is developed in even more striking fashion in sand-dunes. The structure, well seen in Plate XXVI., is termed *current-bedding*, since it owes its origin to changes or oscillations in the direction and strength of the currents, either of water or of wind, which are the agents of transport and deposition. The term *false-bedding* is also used, in reference to the fact that the bedding does not indicate that of the series in which the "cross-bedded" layers occur. The structure is common in littoral and other shallow-water deposits, where there is much shifting and eddying of current-action —as, for example, at the foreset edge of a delta, at the front of a gravel bar, or even in front of a current ripple. In the case of sedimentary deposits a current-bedded sandstone is often directly underlaid and overlaid by evenly-bedded strata, which give evidence of quiet and undisturbed sedimentation. Since the inclination of the laminæ is always downstream, the direction of the currents which deposited the false-bedded material can readily be inferred. In the case of æolian sandstones the successive cross-bedded divisions are separated from one another, not by evenly-bedded strata, but always by planes of erosion. In general current-bedding, whether in sedimentary or in æolian sandstones, is sharply truncated by overlying beds, while it comes in contact with underlying layers by an asymptotic base, and it is thus possible to infer from current-bedded strata the original top and bottom of the stratified series to which they belong.

Grouping of Strata.—Although almost any diversity of strata may be seen in one and the same vertical section, yet, as might have been expected, it is usual to meet with rocks of similar character associated together. Thus, conglomerate is more frequently interstratified with grit and sandstone than with fine argillaceous deposits, while limestone is associated rather with the latter than with coarser grained accumulations. Alternations of different kinds of sediment are quite characteristic of the deposits now forming in lakes, estuaries, etc., but usually the passage is from gravel to grit and sand, and not directly from shingle and gravel to silt and clay. Even in the case already mentioned (see Fig. 5), of a limestone intercalated between underlying and overlying shales, the change from the one to the other is not always so abrupt as it may seem to be. Not infrequently it will be found that the lower shales become more and more calcareous towards the top of the stratum, and that the limestone, in like manner, becomes gradually more and more argillaceous above—so that there is a sort of passage, as it were, from the one kind of rock into the other.

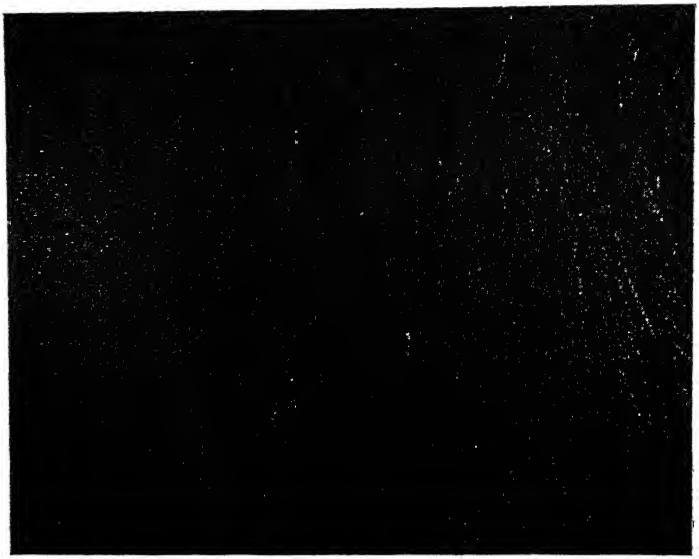
In the silting up of lakes and estuaries, however, it must happen now and again that coarse sediments are laid down directly on the surface of fine accumulations. As a rapidly flowing river pushes its delta outwards, the water naturally shallows over the advancing alluvial cone—in other words, the zone of gravel invades the area where sand was formerly distributed, while the sand in its turn is laid down upon the finer mud and silt. Conversely, when sedimentation takes place over a gradually subsiding area, finer grained deposits continue to advance shorewards and extend over the surface of coarser accumulations. In general, however, such changes are only developed gradually, so that the passage from one kind of sediment to another (either in a horizontal or a vertical direction) will not usually be abrupt. But in the case both of an advancing delta and a retreating coast-line, sudden changes in the character of the deposits must occasionally take place. During floods and freshets, for example, the coarser detritus hurried forward by a river will make an abnormal advance, just as tidal currents will now and again sweep fine-grained sediment further inshore than usual. Sudden changes like this are often accompanied by the process already described as "contemporaneous erosion."

Not infrequently, and usually in rocks which do not show current-bedding (see p. 114), sandstones, grits, and greywackés show *graded bedding*—a particular bed begins at the bottom with relatively coarse material and grades upwards into material which is relatively fine. There may be a succession of such graded beds, or they may be separated from one another by intercalations of other sediments such as mudstones. E. B. Bailey has suggested that graded sandstone beds are often the records of seaquakes—movements communicated to sea-water during disturbances of the sea-floor. The grit, sand, and mud supplied by the unconsolidated clastic materials of the shallow-water belt have been redeposited by such movements in the deeper water beyond the coastal fringe, the larger fragments reaching the bottom in advance of the smaller. Study of graded bedding is a useful auxiliary in determining the original order of succession in beds which are highly disturbed as a result of folding and faulting. When there is gradation from coarser to finer textured sediment in a bed the fine-grained material is towards the original top.

A unique type of lamination, the interpretation of which we owe to the Swedish geologist de Geer, is seen in the *varve-clays* laid down from suspension in the cold waters of glacial lakes. Each layer or varve is double, consisting of a lower, relatively coarse silty portion deposited during the summer melting season, when sediment is being carried into the lake, and an upper portion of very fine clay held in suspension and slowly deposited during the winter. Comparative studies of varve-clay deposits in different parts of Sweden, and later in many other parts of the world, have given valuable evidence regarding late-glacial climatic oscillations and also regarding the time occupied by the recession of glaciers and ice-sheets.

Contemporaneity of Strongly-contrasted Strata.—When we consider that sedimentary deposits are in process of formation over enormous stretches of sea-floor, in shallow and deep water alike, it is obvious that the most diverse accumulations may yet be of contemporaneous origin. It is no more than we might expect, therefore, to find that such rocks as grit and sandstone have been formed on the same sea-floor as limestone. When a series of strata is traced across a wide area we constantly see some of the beds thinning off, and their position in the sequence being occupied by others of a different kind. In this way a great succession of thick-bedded limestones may be split up, as it were, by the intercalation of shales and sandstones, which continuously increase in thickness, while the limestones at the same time gradually get thinner and thinner until at last they disappear, and the whole series of strata then comes to consist of sandstones and shales alone. Similar changes are brought about by variations in the character of the individual beds themselves. Conglomerate, as we have seen, gradually shades off into pebbly grit and sandstone, just as siliceous sandstones pass laterally into fine-grained argillaceous sandstones, and these in their turn eventually merge into shales. So limestone tends to become mixed with clay or sand, and to shade off into calcareous shales or sandstones. Again, coal and ironstone may mutually replace each other; or each may lose its own distinctive character and gradually pass into carbonaceous or ferruginous shale.

PLATE XXVII



1. Rill-marks on Beach at Elie, Fife.

Photo by Dr Laurie.

2. Ripple-marks in Carboniferous Sandstone, Shore near St Monans, Fife.

Photo by Dr Laurie.

[*To face page* 117

An example of a well-marked group of strata which gradually changes its character as it extends from one region to another is supplied by the Lower Oölite of England. This formation may be followed from Somerset through Gloucester and the Midlands to the Humber. Throughout its whole course it rests upon and is covered by well-defined argillaceous beds—the Lias below and the Oxford Clay above. In the south of England the formation is composed essentially of limestones. Followed to the north, however, it becomes more and more arenaceous and argillaceous, until in Yorkshire the limestones of the southern district are entirely replaced and represented by ordinary sandstones and shales with associated coals and ironstones. The transformation of the deposits is not hard to understand. The calcareous accumulations of the south are obviously marine, while the arenaceous and argillaceous deposits of the north are of estuarine and brackish water origin.

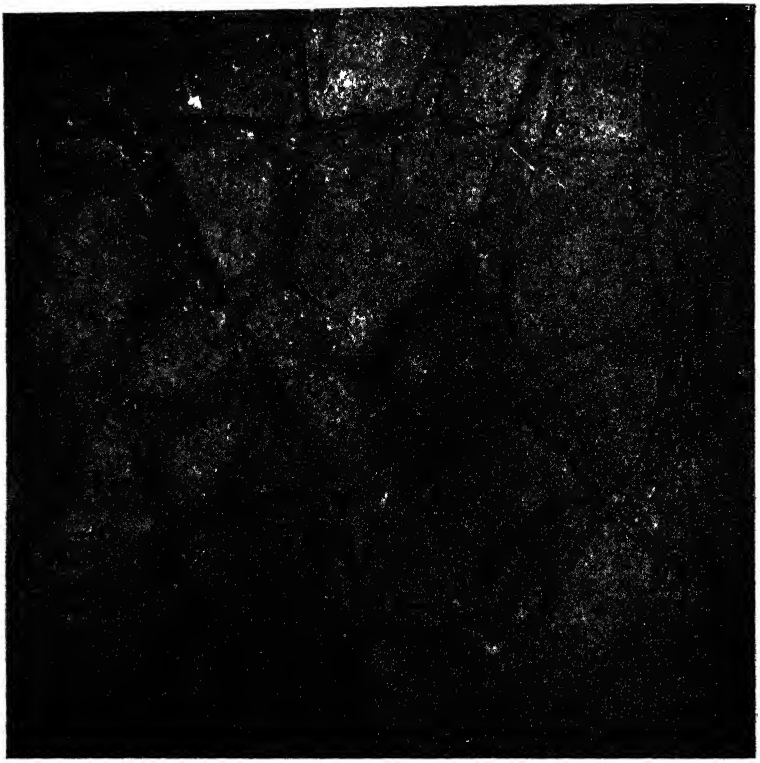
A somewhat similar change comes over the great Carboniferous Limestone formation when it is followed from England into Scotland. In the Mendip Hills the formation consists almost entirely of limestones, which reach a thickness of 3500 feet at least. In Northumberland, the limestone series of the south is represented by a great succession of sandstones and shales, with associated coal-seams and beds of limestone that vary individually in thickness from 7 feet to 150 feet—the entire formation ranging from 2500 feet to upwards of 6000 feet. In Scotland the arenaceous and argillaceous element acquires a very great development—probably not less than 10,000 feet. The only limestones present, however, are some half-dozen beds, varying in thickness from a few feet up to 20 or 30 yards, which, along with numerous seams of coal and ironstone, are intercalated in the upper part of the series.

Surface-markings.—The surfaces of derivative rocks often exhibit interesting markings, among which the most notable are *ripple-marks*. These are sometimes of precisely the same character as the ripple-marks seen on modern sea-beaches (see Plate XXVII. 2 and Plate LXV.). In the shallow water of a sea-beach the ripple-marks slowly advance with the inflowing tide. They usually present a long, gentle slope seawards, and a short and more abrupt slope towards the shore, and may be distinguished as *asymmetrical*. With the ebb-tide, the crests of the ridges tend to be smoothed off or truncated. When the movement of the water is irregular, as between skerries, boulders, etc., the result is the formation of numerous miniature hummocks and dimples, or straggling hollows and rounded ridges. Asymmetrical ripples are formed also on land when sand is shifted by the wind, as in sand-dunes (Plate XVIII.). Ripple-marks of a different type, namely *symmetrical*, originate in deeper water where current action is not effective. They are caused by oscillatory waves, which, when they touch the bottom of a sea or lake, produce a to-and-fro motion of the sedimentary particles. Symmetrical ripples are commonly developed by storm waves at depths up to 300 feet, and exceptionally at considerably greater depths. The crests of ripple-marks of the symmetrical type are sharper than the troughs, and the latter may have minor crests in them. Such ripple-marks, like current-bedding and graded-bedding, afford useful evidence in the determination of the original order of succession in a series of stratified rocks.

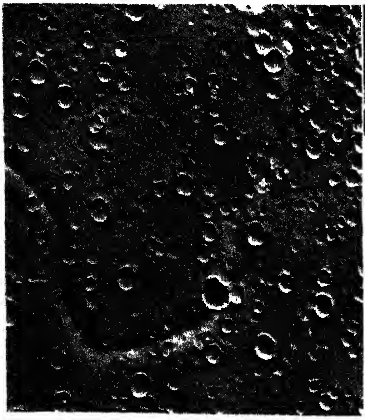
Ripple-marked surfaces are common in many sandstones and argillaceous beds, and often occur one over another throughout a thick series of strata. As each advancing tide effaces old marks, and replaces these by new ones, it is difficult to understand how, under ordinary conditions, a rippled surface of sand can be preserved. Hence it has been surmised that many of the ripple-marked surfaces which appear in rocks of all geological ages may have been produced below low tide-level, in shallow bays or in estuaries, where sedimentation is more or less continuously carried on; so that rippled surfaces might be often preserved by the gentle deposition upon them of fresh accumulations of sediment. However that may be, it seems certain that not infrequently ripple-marked surfaces have really been formed between high and low water. In some cases these have probably been preserved by the deposition over their surface of a thin film of clay. In other cases the rippled sand (often to some extent argillaceous) had become sufficiently consolidated to resist the action of the next incoming tide. It must be remembered, that at low tide on gently shelving shores a wide expanse of beach is laid bare. Exposed to the rays of a hot sun, the fine-grained sand or sandy mud might thus, over wide areas, be so dried and hardened as to resist the obliterating action of the flowing tide, and under such circumstances it is conceivable that surface after surface might be covered up and preserved. Again, on flat shores, wide belts of rippled sand and mud might be exposed between the lines of spring and neap tides. Hence, the surfaces above high-water of ordinary tides might become dried and consolidated before they were eventually covered by newer accumulations. The layer immediately overlying a ripple-marked surface usually shows a more or less perfect cast, which, when removed from its position, is sometimes hard to distinguish from the actual mould or original surface.

Wave-marks. These are seen forming on modern sea-beaches during ebb-tide. They are delicate outlinings which mark the limits reached by the waves as they die out. If the edge of the thin layer of advancing water be observed, it will be seen that it sweeps along with it fine grains of sand, and more particularly particles which, by reason of their shape (mica-flakes) or light specific gravity (coaly matter), are readily carried forward. When the wavelet dies out, these materials are stranded so as to form a miniature ridge, which

PLATE XXVIII



1. Cast of Sun-cracks in Sandstone. One-third natural size.



2. Modern Rain Pits.

3. Rain Pits in Shale.

Photo by T. C. Day.

[*To face page* 119

is often rendered conspicuous by the presence of black carbonaceous matter. Wave-marks of this kind are not infrequently seen on the surfaces of fine-grained sandstones and flagstones, and are good evidence of a beach-formation.

Rill-marks (see Plate XXVII. 1). These are small furrows formed on a sandy or muddy beach by the trickling downwards of little rills during the retreat of the tide. They are occasionally visible on the surfaces of fine-grained sedimentary rocks. When they are numerous and run into each other, they often simulate the appearance of some kind of alga and have not infrequently been described as fossil sea-weeds.

Sun-cracks (Plate XXVIII. 1). Round the shores of inland seas and lakes, the level of which is liable to fall during the dry season of the year, a wide belt of gently shelving ground is laid bare. The same is the case in many river-valleys—broad flats appearing when the rivers are low. Frequently such exposed tracts consist of clay or mud, which, under the influence of the sun, becomes dry and shrinks, so that the surface cracks into polygonal cakes. When the wet season arrives, and the level of the water rises, sand may be deposited over the consolidated and fissured clay, and thus a cast of the cracks will be formed. The same action may take place on low, flat beaches which are exposed to a hot sun during the retreat of the tide. Sun-cracks are thus of common occurrence in many geological systems. The casts usually adhere to the overlying stratum, of which indeed they form a part.

Rain-prints. In like manner the pits made by rain on the surface of fine-grained deposits have occasionally been preserved (see Plate XXVIII. 2, 3). The smooth bedding-planes of argillaceous sandstones, shales, and mudstones are not infrequently pitted in this way, the casts of the pits occurring on the under surface of the overlying stratum. Sometimes the direction of the wind at the time the rain fell is shown by the inclination of the pits in one particular direction. In such cases there is occasionally the appearance of a slight ridge on one side of the pits, as if some of the fine sediment had been flicked out by the drops as they fell.

Animal-tracks, etc. Additional evidence of beach-conditions is obtained from tracks left by animals. Thus, tracks or trails of annelids, molluscs, crustaceans, etc., worm-burrows and castings, and the footprints of reptiles, amphibians, birds, and mammals, have been preserved, usually in fine-grained sedimentary strata. Now and again, also, certain puzzling impressions make their appearance, which have often been described as plant-marks. Possibly some of these may have been formed by sea-weeds waved to and fro by eddying waters, the fronds of the algæ brushing the surface of the sand or mud, and thus drawing or etching curved patterns. Others, again, may represent the trails made by floating algæ or by the tentacles of a jelly-fish. Various surface-markings, which mimic organic structures and have been given generic and even specific names, are probably often of mechanical origin, formed either during or after consolidation of the rocks in which they occur.

CHAPTER VIII

CONCRETIONARY AND SECRETIONARY STRUCTURES

Siliceous Concretions—Flint, Chert, Menilite. Calcareous and Ferruginous Concretions—Septaria, Composite Nodules, Rattle-stones, Fairy-stones, Kankar, etc. Clay-ironstone Nodules, Pyrite, Marcasite, Gypsum, Dendrites. Concretionary Sandstones, Argillaceous Rocks, and Limestones. Concretionary Tuffs. Concretions in Crystalline Igneous Rocks. Secretionary Structures—Amygdales, Geodes, Drusy Cavities.

Concretionary Structures may occur in almost any kind of derivative rock. Sometimes they affect the mass of a rock; at other times they take the form of various sized spherical or lenticular bodies or *nodules*, scattered regularly or irregularly through a rock, or they may appear as more or less interrupted layers or vertical and ramifying veins, or as well-formed crystals. In most cases they owe their origin to the gradual aggregation of mineral matter originally diffused through the mass of the rock in which they occur. Occasionally, however, the mineral matter has been introduced from the outside by percolating water. The commonest concretions are siliceous, calcareous, and ferruginous, and there is a strong tendency in spherical concretions to assume internal radiating and concentric structures.

(*a*) SILICEOUS. Among the most familiar examples of siliceous concretions are the *flints*, which occur so frequently in chalk. Flint nodules are usually irregular in form, and vary in size up to a foot or more in diameter. They are white externally and brown to black internally. They often enclose or partially enclose fossils, more particularly sponges. Usually they are arranged in lines that coincide with the bedding-planes of the chalk. They may coalesce to form more or less interrupted sheets or seams of flint (some three or four inches thick), which follow the bedding of the chalk, or may traverse it, as irregular vertical or ramifying veins. In the older limestones *chert* plays much the same part as flint in chalk, and is probably, like the latter, in many cases of organic origin. Now and again, however, it may have been a deposition from thermal water. In such cases it occurs as thin laminæ, interleaved with similar laminæ of limestone—the layers being often highly puckered, crumpled, or confusedly contorted and involved, as if the deposits had been disturbed by the bubbling-up of spring-water before they had become quite solidified.

These appearances, however, may be otherwise accounted for. The siliceous solution may have been originally in a colloid or jelly-like condition, containing some percentage of water. Thus, when the mineral began to lose its water and solidify, the contraction of its bulk would give rise to much distortion and confusion—later accretions of silica filling up any fissures or cavities thus produced. Concretions of chert are not uncommon in some argillaceous rocks, and reniform *menilite* appears now and again in marls. Even sharp crystals of *quartz*, generally of small size, have occasionally been developed in marly clay.

(*b*) CALCAREOUS and FERRUGINOUS. Spherical and nodular calcareous and ferruginous concretions are characteristic of many argillaceous rocks and of some sandstones. In laminated clay the mineral solutions have made their way most readily along the planes of sedimentation, so that the resulting concretions are usually somewhat lenticular, and often assume the shape of flattened spheroids. When numerous, they not infrequently coalesce so as to form irregular concretionary bands or layers. Very often, however, they are scattered sporadically through the beds in which they occur. In homogeneous clay rocks, without apparent lamination, the concretions are usually either spherical or variously shaped, and often irregularly dispersed. Frequently they have formed round a nucleus, which may consist of mineral matter, but is more commonly of organic nature, such as a shell, a coprolite, a fish, a fragment of plant, etc. A concretion may be compact and homogeneous throughout, or may consist of concentric shells, or while externally compact it may be much cracked and fissured internally. The cracks are widest towards the centre of a concretion, and die out towards its circumference, as if the interior had contracted after the outside had dried and become consolidated. They are often partially or completely filled with subsequently introduced mineral matter, usually calcite. Concretions of this kind are known as *septaria* or *septarian nodules*, in allusion to the septation or partitioning of the interior (see Plate XXIX. 1). Septaria are commonly either calcareous or ferruginous. Occasionally, concretions consist of concentric shells of different chemical composition. In a nodule, composed for the most part of ferruginous matter, one or more of the shells may be calcareous; or the core or kernel may be calcareous and the external shells ferruginous.* Owing to the subsequent action of percolating water, the calcareous portions may be completely removed in solution. In this way, by the removal of a calcareous layer from the interior of a nodule, a central ferruginous kernel becomes detached, and rattles when the concretion is shaken (*Klapperstein*, or Rattle-stone). When a calcareous core is entirely dissolved, a nodule, of course, becomes hollow. Many nodules, however, are rendered hollow, simply owing to the contraction of the interior after the outer shell has dried and hardened.

Concretions of the several kinds referred to in the preceding paragraph are all obviously of secondary origin—they are superinduced structures. This is shown by the fact that the planes of sedimentation can often be seen passing through them, and never curving over them, as would have been the case had they been loose stones and boulders covered up while

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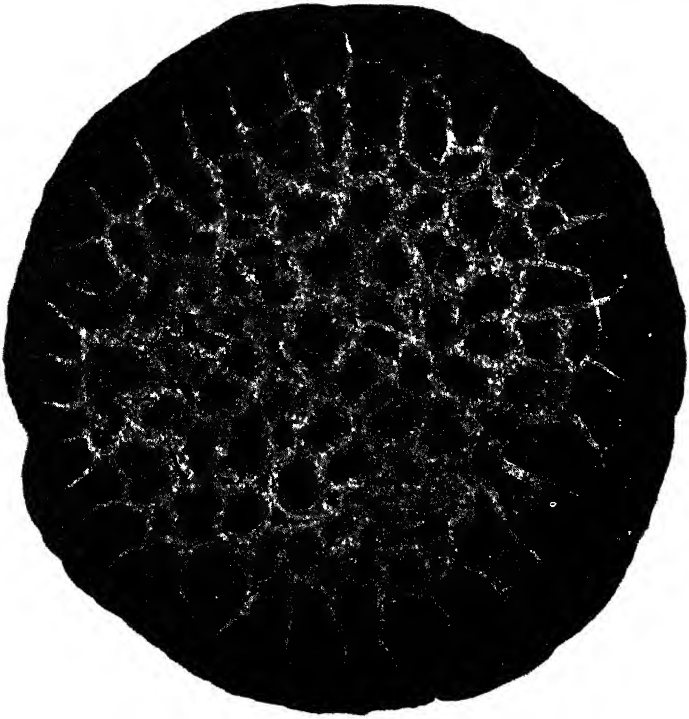
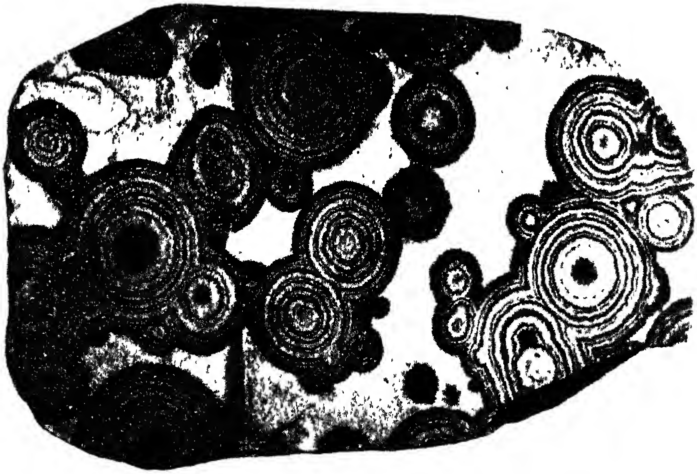
* Occasionally one or more of the concentric shells may consist of oxide of manganese (psilomelane).



1. SECTION OF SEPTARIAN NODULE (CLAY-IRONSTONE). About one-half natural size.



2. SECTION OF SPHERICAL CONCRETIONS (FERRUGINOUS) IN SANDSTONE.
About one-half natural size.

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lying on lake-floor or sea-bottom. Among familiar examples of concretionary calcareous nodules are the so-called *fairy stones* so frequently met with in alluvial clays. In Germany they are common in loess, and are known to the country-folk as "Löss-püppchen, Lössmännchen," etc., and as "Marlekor" (Kobolds' toys) or "Näkkebröd" (Nixies' bread) in Sweden. Similar calcareous concretionary nodules termed "kankar" are abundantly developed in many of the black cotton soils of India. Reference may also be made to the curious calcareous concretionary structures which occur in the Tertiary sand of Fontainebleau, near Paris. These frequently take the form of single crystals of calcite, or of groups and aggregates of rhombohedral crystals. Ferruginous concretions are well represented in this country by the balls and nodules of *clay-ironstone* (sphærosiderite) that occur so abundantly in the black shales of the Carboniferous System. They vary in size from a hazel-nut to flattened spheroids measuring two or three feet across, but these last are not common. Many contain a fossil at the centre, while others seem to consist wholly of inorganic materials. A large proportion, it may be added, are septarian. As calcareous and ferruginous concretions alike tend to be developed in the direction of the bedding-planes of the rock in which they occur, it frequently happens that contiguous nodules become fused together, so as to form more or less continuous seams of limestone or of ironstone, as the case may be. Sometimes such seams maintain a uniform thickness, but more usually they are lumpy, thickening and thinning irregularly. Concretions of disulphide of iron (*Pyrite* and *Marcasite*) are of frequent occurrence in sandstone, clay, chalk, and coal. They vary in size from minute grains up to nodules two or three inches in diameter. In the form of nodular concretions marcasite is much more common than pyrite, the concretions having usually an internal, fibrous, radiating structure. Now and again marcasite, however, assumes a crystalline form, as in the flat, spear-headed "twins" which are seen in the chalk deposits of Dover and Folkestone. Pyrite does not occur so commonly in nodules as marcasite, but has a much wider distribution in the crystalline form, crystals and crystalline aggregates appearing in many kinds of derivative rocks, either dispersed through a rock-mass or lining its minute cracks and fissures. As sporadic crystals or groups of crystals it often appears in clay-slate, but such occurrences fall to be considered under the head of metamorphism. No hard-and-fast line can be drawn between the changes which produce concretions and concretionary structures in "unaltered" rocks, and those which have induced the aggregation and crystallisation of mineral matter in certain "altered" and "metamorphic" rocks.

Sulphate of lime is not so often met with in concretions as carbonate of lime and ferruginous compounds. In some clay-rocks, however, *gypsum* concretions are common enough. Sometimes these appear as large perfect crystals and twins of the mineral, but more frequently as lenticular nodules or layers, an inch or more in thickness.

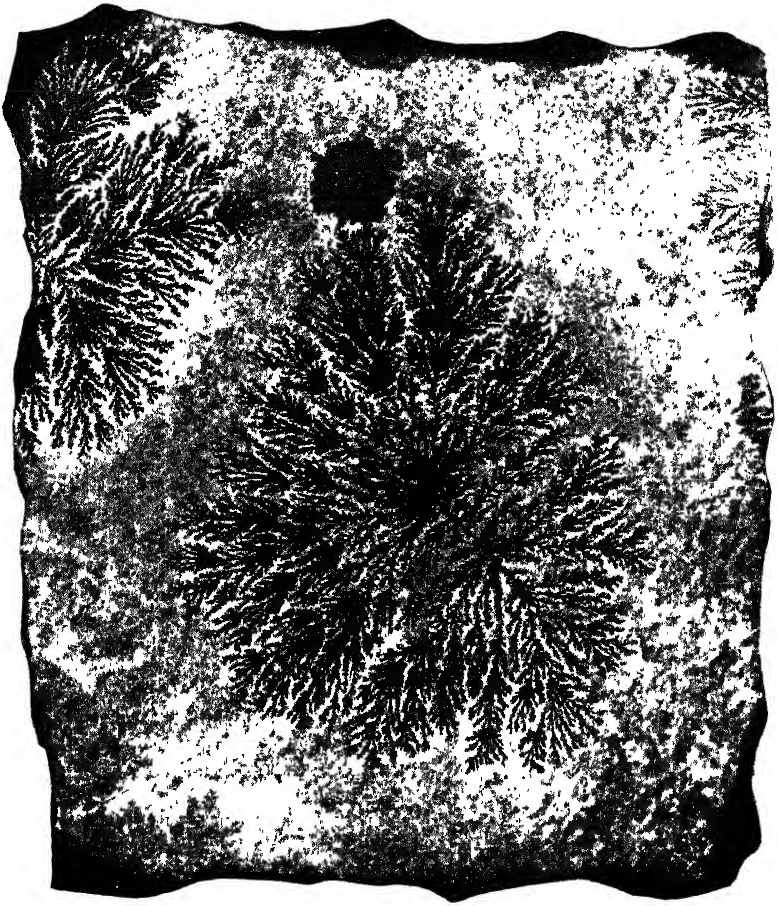
The oxides of manganese and iron occur not only in nodular forms, but frequently appear as thin films coating the surfaces of the natural division-planes of rocks, such as joints and bedding-planes. They usually assume delicate plumose or plant-like forms resembling sprigs of moss, etc., and hence are termed *dendrites* or *dendritic markings* (see Plate

XXX.). Although usually appearing only on division-planes, now and again they ramify through the substance of fine-grained rocks, such as certain limestones, on sections of which the markings often simulate belts of trees, hedgerows, etc. (*landscape-marble*).

CONCRETIONARY ROCKS. Not only do mineral solutions tend to form concretions of various kinds in rocks, but the rocks themselves have not infrequently acquired a concretionary structure. Some *sandstones*, for example, seem to be largely composed of aggregates of ball-like or larger spheroidal masses. Few sandstones, indeed, do not in places show some indications of this concretionary structure. The spheroids are now and again enclosed in dark brown ferruginous crusts, the rock within being often bleached, and sometimes even reduced to the condition of loose sand. When sandstone of this character is exposed by quarrying, the freshly cut rock may show concentric bands of a dark brown or red colour, some of which may be an inch or less in width, while others may exceed several feet. The origin of the structure is obscure. The ferruginous matter may have been introduced by percolating water, but some of it at least has been abstracted from the sandstone itself. The concentric shells of ferruginous matter shown in Plate XXIX. 2 are not hard to explain, and their mode of formation may throw some light on that of the larger concretionary masses to which reference has just been made. They owe their origin undoubtedly to the presence of disseminated granules or crystals of some ferruginous mineral, almost certainly pyrite or marcasite. By the action of water soaking into the stone the mineral is broken up chemically, and a ferruginous solution formed, which spreads outwards as a drop of ink does on blotting-paper. Evaporation taking place around the outer margin of the solution, iron-oxide is precipitated, and the first ring or shell is formed. The process is repeated by the formation of a second shell inside the first, and thereafter the production of successive concentric shells is continued, each forming inside its predecessor, until the ferruginous solution is exhausted. In some cases, a portion of the ferruginous mineral at the centre may remain, but it is usually so small and so much altered that its original character is hardly recognisable. Other kinds of concretionary structures are frequently met with in sandstones. Small quantities of carbonate of lime or carbonate of iron, diffused through the rock, tend to aggregate so as to form irregular concretionary masses of sandstone, which are much harder than the surrounding rock. Cracks and crevices in concretionary masses of this kind are often filled or lined with crystalline siderite or calcite, as the case may be. The hardened rock (known as "kingle" in Scotland) breaks with a splintery fracture, and is rejected by the quarrymen as unsuitable for building purposes.

Argillaceous rocks hardly less frequently assume concretionary forms. Now and again a whole bed of shale may exhibit the structure—the rock appearing to be composed of an aggregate of various sized spheroids. The spheroids usually show a concentric arrangement—the concentric shells being in some cases separated from each other by thin films of ferruginous matter.

Calcareous rocks often enough acquire a concretionary structure—the most pronounced examples of the kind being furnished by dolomitic or magnesian limestone, as already described (p. 71). Reference may also be



DENDRITIC MARKINGS (PSILOMELANE) ON LIMESTONE. Two-thirds natural size.

made to the oölitic structure of certain limestones, calcareous tufas, and ironstones, which, however, in most cases is original (see pp. 71, 73, 75).

Concretionary structures, comparable to those that characterise so many derivative rocks, can hardly be said to occur in igneous rocks. Exception, however, must be made of the *tuffs*, in many of which concretionary ferruginous and calcareous nodules occur, while now and again tuff itself may exhibit concretionary structure, such as that seen occasionally in argillaceous shales. But the concretionary structures that affect many crystalline igneous rocks differ from those which occur in derivative rocks in being original and not superinduced. For example, the dark, irregular shaped aggregates of ferromagnesian minerals which appear in many granites, gabbros, and other plutonic masses, and the sporadic nodular masses of olivine so frequently met with in basalt, are in some cases early segregations from the original molten magma.

Secretionary Structures.—These are especially characteristic of certain types of igneous rocks, but may occur in almost any kind of rock having a cellular or cavernous structure. They consist of mineral matter which has been deposited on the walls of cavities, usually in successive layers, and thus they may be said to increase from without inwards. In this respect they differ from concretions which owe their origin, as already explained, to the aggregation of mineral matter round a certain point, so that they grow from within outwards. Secretions are typically represented by the mineral matter which so often occupies the vapour cavities of lava-form rocks. As these cavities are usually somewhat flattened from having been drawn out in the direction of flow, the subsequently introduced secretions are often almond-shaped. Hence they are termed *amygdales*, and the rock itself is said to be *amygdaloidal*. Such cavities vary in size from mere pores up to hollows measuring many inches in diameter. Sometimes the walls are lined with a mere film of mineral matter; in other cases the cavities may be largely or completely filled up (see Plate I. 1). A secretion may consist of one and the same kind of mineral matter, or of successive bands of various minerals, and some of these bands may be distinctly crystalline, while others are cryptocrystalline or apparently amorphous. In other cases a cavity may be occupied by an irregular aggregate of different minerals—all more or less well crystallised. A hollow secretion, readily separable as a nodule from the rock in which it has been formed, is termed a *geode*; while *druse* is the term applied to a cavity lined or studded with crystals. Nevertheless, "geode" and "druse" are sometimes used interchangeably. It is common, for example, to apply the term geode to siliceous secretions occurring in the form of hollow spheroids or balls, in such rocks as limestone and highly decomposed amygdaloids, from which the ball-like bodies are readily detached. "Geode," therefore, refers rather to the secretion than to the cavity in which it occurs. "Druse," on the other hand, has reference not only to a particular character of the secretion, but to the fact that it occupies a cavity. Hence, geologists often speak of *drusy cavities*, meaning by that simply crystal-lined hollow spaces.

The secretions occurring in crystalline igneous rocks may be (a) *original or synchronous*, or (b) *subsequent or superinduced*. As types of the former (*original*), may be cited the drusy cavities in granite (Plate IX. 2), which are partially filled with well-crystallised examples of one or more of the original constituents of the rock. Obviously, such secretions must be synchronous with the formation of the granite. Analogous to the drusy cavities in granite are the mineral-lined or mineral-filled cavities of irregular shape characteristic of some acid igneous rocks (rhyolite). These, it can hardly be doubted, are deposits from heated solutions, formed before the rock in which they occur had cooled. Probably of similar origin (at least in some cases) are the zeolites, which occur so abundantly in the vapour cavities of certain basic rocks, as, for example, the fine drusy cavities of the Tertiary basalts of the Færöe Islands and Iceland.

Among *subsequent* secretions, the most typical are the amygdales referred to above. While the formation of these may sometimes be almost synchronous with that of the rock in which they occur, there can be little doubt that in many cases the amygdales are of subsequent origin, the mineral matter having been introduced by percolating water long after the cellular rock had cooled and solidified. Amygdaloidal rocks are usually more or less decomposed, the amygdales consisting of material derived from the breaking up of one or more of the original rock-constituents, especially the feldspars.

The minerals of most frequent occurrence in amygdaloidal cavities are calcite, chalcedony (agate), quartz, zeolites, green-earth, etc. As siliceous secretions are more durable than the igneous rocks in which they occur, they are often found in the soils and subsoils resulting from the decomposition of amygdaloidal rock, and under such conditions they are, as already indicated, often termed *geodes*.

CHAPTER IX

INCLINATION AND CURVATURE OF STRATA

Dip—Apparent and True. Terminal Curvature. Outcrop influenced by Angle of Dip and Form of Ground. Strike. Curvature of Strata—Monoclinal Folds, Quaquaversal and Centroclinal Folds, Normal or Vertical Folds, Inclined Folds, Inversion, Recumbent Folds, Fan-shaped Structure, Contorted Strata.

IN considering the formation of rock-beds, some incidental reference was made to the fact that strata, which must originally have been horizontally disposed, are now frequently inclined, and even flexed, folded, and contorted. These and other superinduced structures now fall to be described in more or less detail.

Dip.—The *dip* is the inclination of beds down into the earth, and is measured in degrees by the angle between the plane of the strata and the plane of the horizon. The instrument employed for this purpose is called a *clinometer*—a graduated arc with pendulum. For general use it is convenient to have the clinometer combined with a *compass*—with the latter one takes the *direction*, and with the former the *degree* or amount of dip.* When strata are so exposed that the line of greatest inclination can be observed, the direction and amount of dip are readily ascertained. If the surface of an exposed bed be smooth and even, we have only to place the clinometer upon it, taking care that the edge of the instrument is arranged in the direction of greatest slope (*i.e.* the direction in which water would flow if poured upon the surface), and that the pendulum is swinging freely. The pendulum points, of course, to the degree or amount of dip. If the surface be not very smooth, one may lay one's hammer or walking-stick upon the rock in the line of dip, and thus provide a longer edge on which to place the clinometer—the object being to get as true an average as possible for the whole surface. But to insure this, it is always advisable to check the result thus obtained by taking the angle of dip at a little distance from the section exposed. To do so, the observer, standing back from the section, holds the clinometer within a short distance of his eye, and in such a position that the straight edge of the instrument shall coincide with the lines of the dipping strata. The distance at which one should make an observation of this kind will depend largely on the height of the exposed section. If the height be only a few yards the dip may be measured at no greater distance than the height. But if the section be much higher the observer must stand proportionally further back, so that the edge of the clinometer may coincide with as long a stretch of the lines of bedding as possible. In this way we usually get, by means of one observation, a more reliable average than we should if we had taken the average of twenty observations made by placing the clinometer directly on the rock-surface. Even in the case of false-bedded strata it is often possible, by standing well back from the section, to get a good average dip for the whole series. But when the actual surfaces of the bedding-planes are not visible, the beginner may easily be deceived as to the true position of the strata. The lines of bedding which are seen traversing the face of a cliff do not necessarily indicate the true direction and amount of dip. Beds that are really inclined may even appear to be horizontal. In the accompanying section, for example (Fig. 10), the beds at *a* seem to be horizontal, when in reality they dip at a considerable angle, as shown at *b*—where the cliffs run in the direction of the true dip—the direction and amount of which can therefore be readily determined. Not infrequently, however, cliffs and other

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* See Appendix C.

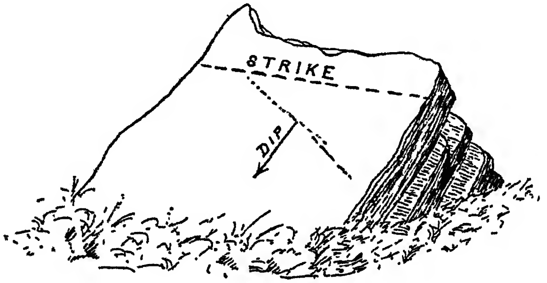
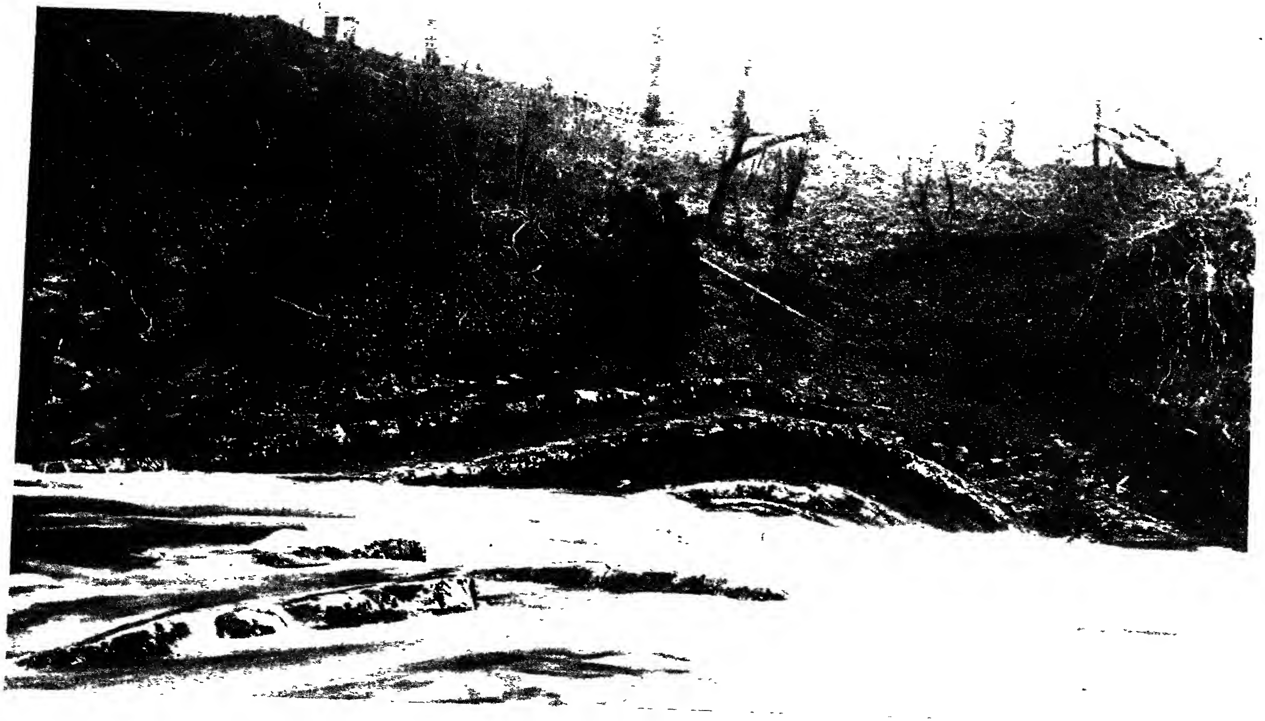


FIG. 9.—DIP AND STRIKE OF STRATA.

PLATE XXXI



ANTICLINAL FOLD IN LIMESTONE, PENTON BRIDGE, LIDDEL WATER, DUMFRIESSHIRE.

Photo by H.M. Geological Survey.

[*To face page* 129

cuttings or sections traverse the dip of the strata obliquely, and when such is the case, the apparent dip shown by the edges of the exposed beds does not indicate either the exact direction or the full amount of the true dip, which is always greater than that of the *apparent* dip. When the observer suspects that the inclinations exposed in two adjacent sections are only apparent dips, he may yet find the true direction by geometrical methods. As a rule, however, an apparent dip can rarely, if ever, deceive one who is not content to view sections from a distance. Close examination will seldom fail to discover on even the smoothest of cliff-faces, irregularities—ledges, depressions, entering and re-entering angles, etc.—in one or other of which the upper or under surfaces of the bedding-planes are almost sure to be disclosed.

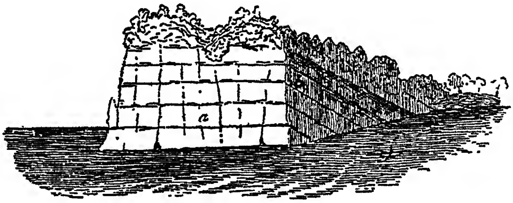


FIG. 10.—APPARENT AND TRUE DIP.

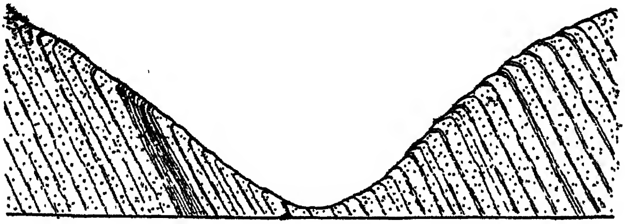


FIG. 11.—TERMINAL CURVATURE IN STEEPLY INCLINED STRATA.

In hilly and mountainous tracts, the exposed ends of strata often present a fallacious appearance of dip, which has occasionally led to mistakes. The appearance referred to is known as "terminal curvature" or "surface creep," and is illustrated in the accompanying figures (Figs. 11, 12). An observer ascending the mountain-slopes shown in the diagrams might quite well be deceived by the apparent dip of the beds, if it did not so frequently happen that the true dip of the rocks in such a region is usually exposed in numerous torrent-tracks and gullies. The origin of terminal curvature is obvious enough—being solely the result of weathering. Rain-water insinuates itself between the bedding-planes, and the strata are thus exposed not only to its chemical and mechanical action, but to the more powerful action of frost. The latter tends to force the beds apart—movement taking place chiefly in the line of least resistance, which, of course, is downhill. In this way the edges of the beds are gradually turned over, so as to present an apparent dip which may be exactly opposite to the true inclination of the strata. In high-lying districts this inverting process is often aided by the movement of massive heaps of snow, and by the downward creeping of water-saturated sheets of earthy rock-débris, which tend to drag forward the edges of the beds in the direction of movement.

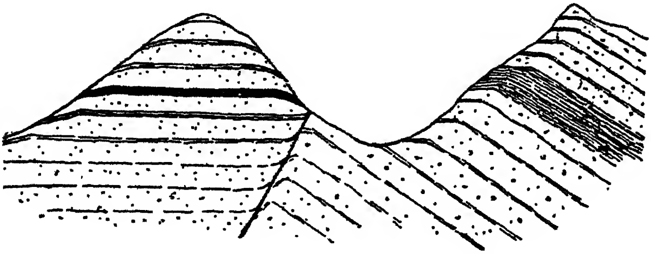


FIG. 12—TERMINAL CURVATURE IN HORIZONTAL AND INCLINED STRATA.

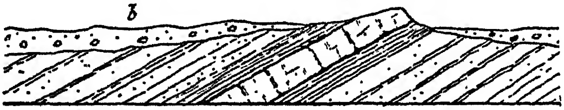


FIG. 13.—OUTCROPS CONCEALED UNDER BOULDER-CLAY, *b*.

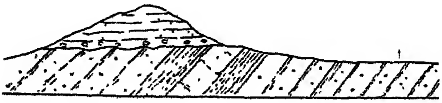


FIG. 14.—OUTCROPS CONCEALED UNDER OVERLYING STRATA.

Outcrop is the term applied to the edges of the strata which appear at the surface. An outcrop may be exposed or visible, or it may be covered and concealed under younger accumulations (see Figs. 13, 14). As a rule, the direction of the outcrop is influenced partly by the inclination of the strata and partly by the form of the ground. When the beds are quite horizontal, every change in the configuration of the surface must affect the direction of the outcrops, which in such a case behave as contour-lines or lines of equal elevation, and follow all the irregularities of the ground. When strata are gently inclined the outcrops are also strongly affected by the shape of the surface; but this influence gradually lessens as the angle of dip increases, the outcrops, as the beds approach verticality, becoming more and more persistent in direction, and being less and less modified by changes in the form of the ground. When the strata are actually vertical or *standing on end*, the outcrops then run in straight lines across hill and dale, being practically independent of the surface features.

A little consideration will show that the *breadth* or *width of an outcrop* must similarly be influenced by the angle of dip and the form of the ground. In the case of horizontal beds the uppermost stratum, although it may be quite thin, must frequently occupy a relatively wide area and form a broad outcrop. With inclined strata, it is obvious that the outcrops will be broad or narrow according as the dip is low or high—the lower the angle of dip the wider the outcrop (see Fig. 15). As the dip increases, the width of the outcrops gradually diminishes until the strata become vertical, and then the width of outcrop can be no more than the actual thickness of the beds.

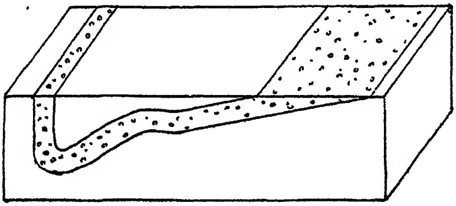


FIG. 15.—WIDTH OF AN OUTCROP AFFECTED BY ANGLE OF DIP.

The diagram on page 132 (see Fig. 16) may suffice to illustrate how the width of an outcrop is affected by surface features. The beds 1, 2, 3, as seen in section, are of equal thickness, but their outcrops, owing to the shape of the ground, vary much in width. Bed 1, appearing upon relatively flat land, yields a broad outcrop; bed 3, forming the surface of a gently inclined plateau, covers a much wider area; while bed 2, coming out on a steep slope, gives an outcrop only slightly broader than the true thickness of the stratum.

Strike is a line drawn exactly transverse to the dip. Thus beds with an east dip have a north and south strike. The strike rarely coincides with the outcrop; usually it only does so in the case of vertical strata, the outcrops of which are not affected by the form of the ground. Now and again, however, when the edges of strata inclined at any angle crop out upon a level plain, outcrop and strike may coincide. The term strike is generally used by geologists when they are referring to the average direction of an outcrop. Thus a great succession of strata having a persistent or dominant dip, say towards the north, are said to have an east-and-west strike, no matter how sinuous and irregular the outcrops may be (Fig. 17). Again, when two series of strata with discordant dips occur in juxtaposition, the one set is said to *strike at* or *against* the other. The conditions referred to are shown in the ground-plan (Fig. 18), where the cause of the discordance is the presence of a fault (see Chapter XI.).

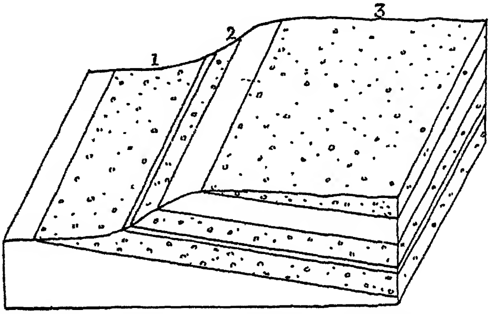


FIG. 16.—WIDTH OF OUTCROP AFFECTED BY FORM OF GROUND.

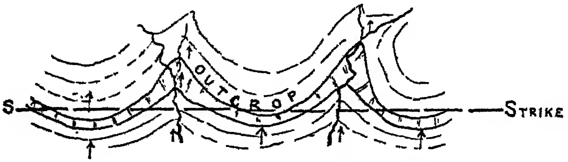


FIG. 17.—OUTCROP AND STRIKE.

Curvature of Strata.—Inclined beds are usually, but not always, parts of large curves or undulations. Under certain conditions, as in the case of deltas, we may have a succession of imbricating and interosculating beds, all the members of the series showing a general dip in the direction followed by the sediment-transporting current. Further, it is obvious that the lower beds of a great succession of strata accumulated in a basin-shaped depression, must be more or less inclined, according as the floor of the basin shelves rapidly or gradually. But with continuous sedimentation the inequalities of lake-bottom and sea-floor must eventually be obliterated, and the bulk of the deposits come to occupy an approximately horizontal position. There is little reason to doubt, therefore, that all the great systems of marine sedimentary strata were originally for the most part arranged in successive horizontal layers and sheets. With such exceptions as those referred to above, the inclined position which strata now so frequently occupy must be due to subsequent crustal deformation. Strata originally horizontal have been thrown into gentle undulations and sharper folds, and the tops of such folds and undulations having been gradually denuded away, the truncated ends of the strata now crop out at the surface.

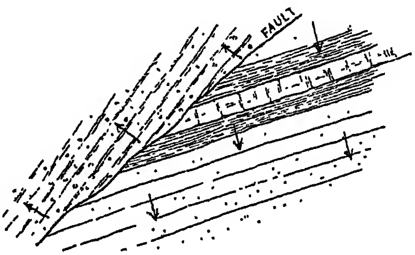


FIG. 18.—STRATA STRIKING AT EACH OTHER.

As might have been expected, folds present every degree of complexity Some are broad, the limbs making a large angle with each other ; such folds are said to be *open*. When, on the other hand, the folds are narrow and compressed, with the limbs parallel or nearly so, they are described as *closed*. In some folds the strata are but slightly disturbed —they simply rise and fall in gentle undulations—in others the beds may be twisted, contorted, and confused in the most intricate manner.

Monoclinal Flexure.—The simplest kind of flexure is the monocline. This structure is met with chiefly in regions of horizontal or gently inclined strata. It may be shortly defined as a sudden dip or abrupt increase of dip followed by an equally abrupt return to the former horizontal or gently inclined position (see Fig. 19). Frequently the strata in the limb of a monoclinal fold appear attenuated (see

Fig. 20), as if they had either been compressed laterally or drawn out upwards or downwards. As we shall see later on, this attenuation becomes still more pronounced until the limb of the flexure vanishes and is replaced by a fault or dislocation.

Quaquaversal and **Centroclinal Folds.**—Now and again, in regions of gently inclined strata, we encounter dome-shaped and basin-shaped structures. When the strata are dome-shaped they are said to have a quaquaversal dip, *i.e.* they are inclined outwards in all directions from a common point (see Fig. 21). The converse of this structure is seen in a centroclinal fold—the beds dipping inwards from all directions towards a central point (see Fig. 22). But symmetrical or complete quaquaversal and centroclinal folds are of somewhat rare occurrence, and may be looked upon as accidental modifications of normal anticlinal and synclinal folds.

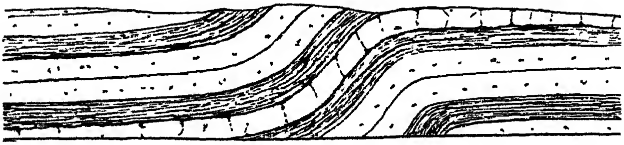


FIG. 19.—MONOCLINAL FLEXURE.

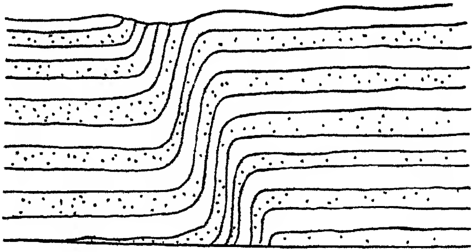
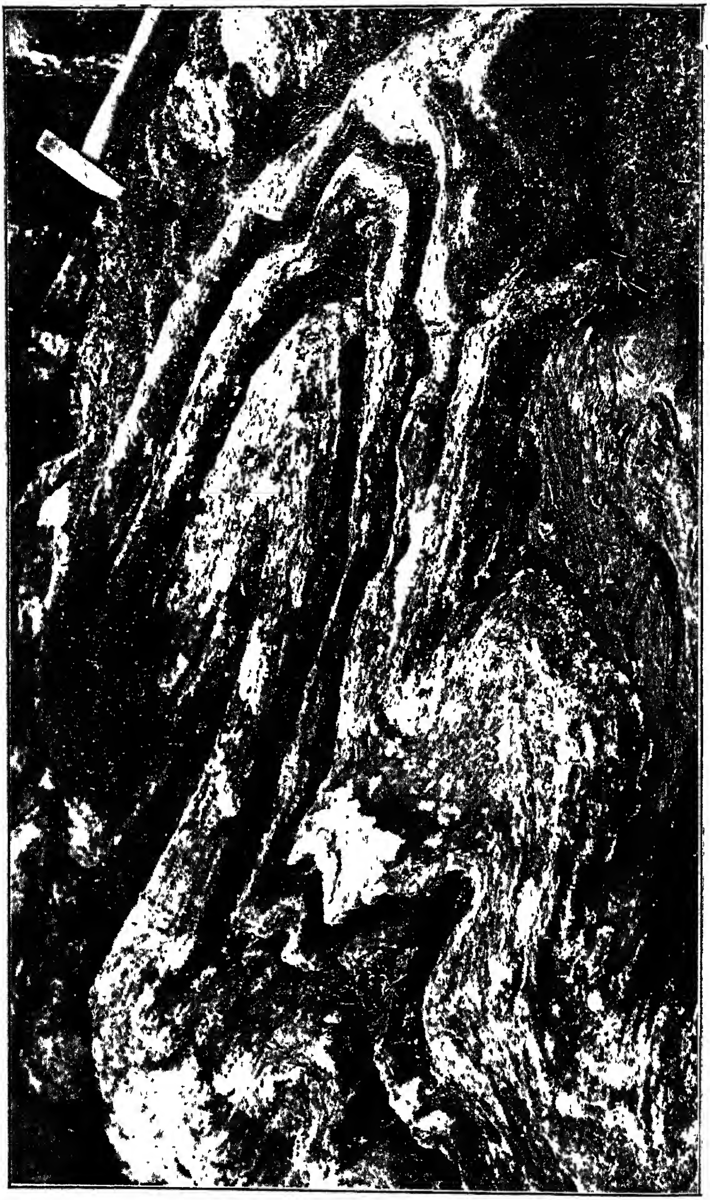


FIG. 20.—MONOCLINAL FOLD SHOWING THINNING OF BEDS IN THE FOLD.

Normal or **Vertical Folds.**—Strata, as a rule, are folded along axes, an axis being defined as the intersection of the axial plane with the crest or trough of the fold (see Fig. 23). The axial planes of normal folds are approximately vertical and usually extend in straight or gently curving lines. They vary much in length—from a hundred yards or less to many miles. When the strata dip away from the axial plane on either side at approximately the same angle, the structure is

PLATE XXXII



CONTORTED SCHISTS, ETC.—BEN VRACKIE.

Photo by H.M. Geological Survey.

[*To face page* 135

known as an **Anticline** or *Saddle-back* (Plate XXXI.). The converse structure, in which the strata dip in from either side at equal angles to the axial plane, is termed a **Syncline** or *Trough* (see Figs. 23, 24). When the inclination of the strata is moderate, individual anticlines and synclines do not usually extend for any great distance. A wide region of gently undulating strata often recalls the appearance presented by a slightly rumpled tablecloth—in which the individual wrinkles, sometimes short, sometimes long, succeed each other at inconstant intervals; and while tending, perhaps, to run in a particular direction, are yet frequently straggling and irregular. But when the strata are inclined at higher angles anticlinal and

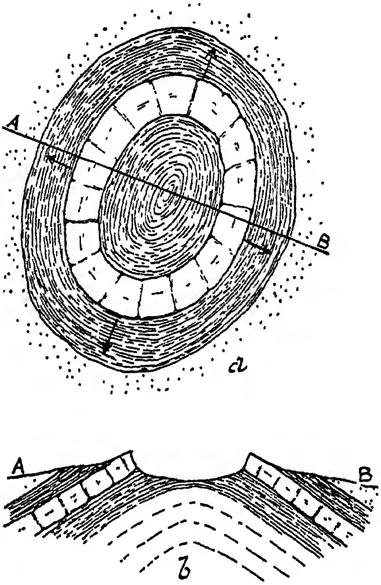


FIG. 21.—QUAQUAVERSAL FOLD.
a, ground-plan; *b*, section along line A—B.

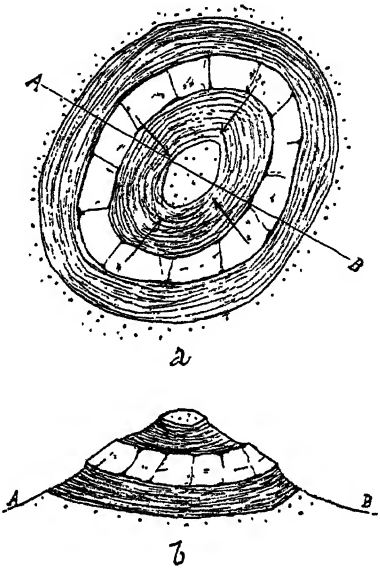


FIG. 22.—CENTROCLINAL FOLD.
a, ground-plan; *b*, section along line A—B.

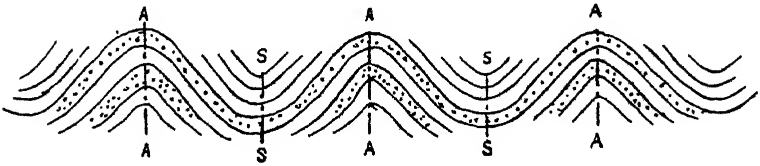


FIG. 23.—NORMAL FOLDS. AA ANTICLINES; SS SYNCLINES.
The upright dotted lines indicate the vertical axial planes.

synclinal folds are apt to extend for longer distances and to preserve their parallelism more or less persistently. When folding is well developed, it is often possible to follow the axes of individual anticlines and synclines throughout their whole extent. Each fold begins at zero—forming, at first, a quite insignificant "lirk" or crease; little by little, as we follow the axis, the dip of the strata augments until in a longer or shorter distance the maximum inclination is reached, after which the dip usually begins to decrease, and finally the fold dies away. Not infrequently, however, folds increase and diminish in an irregular manner—a great system of parallel anticlines and synclines often consisting of a series of dovetailed and interlocked folds of variable width and extent. The axis of a fold, as we have seen, does not always maintain the horizontal position. The angle which the axis makes with the horizontal determines the **pitch** of a fold. The pitch is of course given by the angle of dip of the beds measured along the axis. On a flat, or nearly flat, surface of erosion the outcrop of a bed at the termination of a pitching syncline

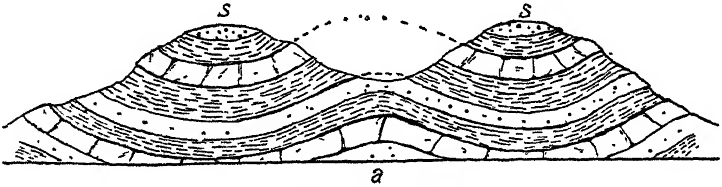


FIG. 24.—NORMAL OR VERTICAL FOLDS.
a, anticline; *s s*, synclines.

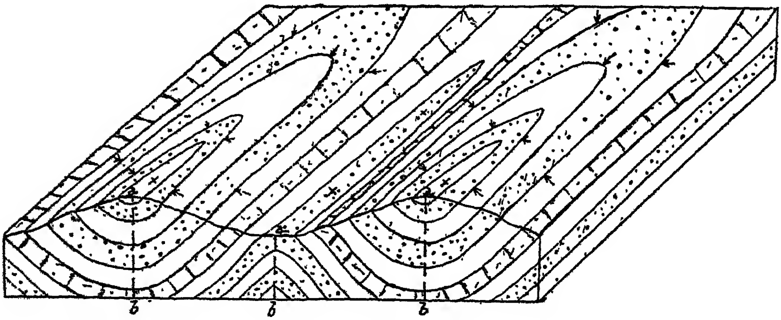


FIG. 25.—MODEL OF DENUDED SYNCLINAL AND ANTICLINAL FOLDS.
a—b, *a—b*, Positions of axial planes of folds.

or anticline has the shape of a horseshoe. This is well seen in the case of the two denuded synclines shown in Fig. 25.

When folded strata have been for a long period exposed to denudation, the original crowns or crests of the anticlines have invariably disappeared—the ridges have been gradually lowered by denudation. On the other hand, the synclinal structure has evidently offered greater resistance to the forces of decay, for not infrequently we find that hills are built up of trough-shaped strata (Figs. 24, 25). But although the original tops of all anticlinal ridges have, as a rule, disappeared, and synclinal troughs have also been reduced, geologists still speak of these structures as if they were perfect folds. Fig. 25 represents the model of two synclines with intervening anticline—the arrows indicating the direction of the dip. The dotted lines (*a b*) are the traces of the axial planes of the folds. The section shows the geological structure and the relation of that structure to the surface features.

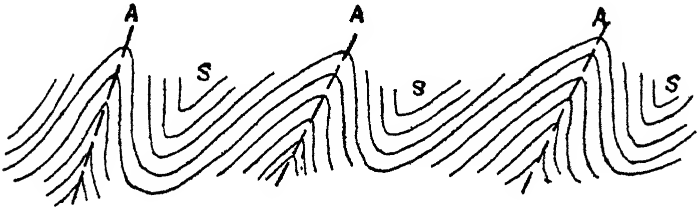


FIG. 26.—FOLDS WITH INCLINED AXIAL PLANES.

Inclined Folds.—When the axial plane of a fold is not vertical, the fold is said to be inclined or asymmetrical (Plate XLIII.). The inclination may be very slight—so slight that the strata on either side of the axis may have much the same angle of dip; or the axial plane may depart so far from the vertical as to be actually horizontal, and the fold then lies on its side. Between these extremes every degree is encountered. As a rule, inclined folds are closely compressed, the limbs flattened against each other, and the crowns of the arches usually somewhat pointed (Figs. 26, 27). Other typical forms are represented in the accompanying illustrations (Figs. 28-30). When the axial plane is so much inclined that one limb of the fold becomes doubled under the other, we have the structure known as an **Overfold** (see Figs. 27, 28). In folding of this kind the strata in the lower limbs of the anticlines are necessarily turned upside down, and hence the structure is frequently termed **Inversion.** Inclined and closely compressed normal folds not infrequently occur together, but in regions of highly inclined and vertical strata the flexures are usually inclined and for the most part are overfolds. In such cases the successive axial planes very often incline for long distances in the same direction—the flexures which show this arrangement being termed **Isoclinal folds** (see Figs. 29, 30).

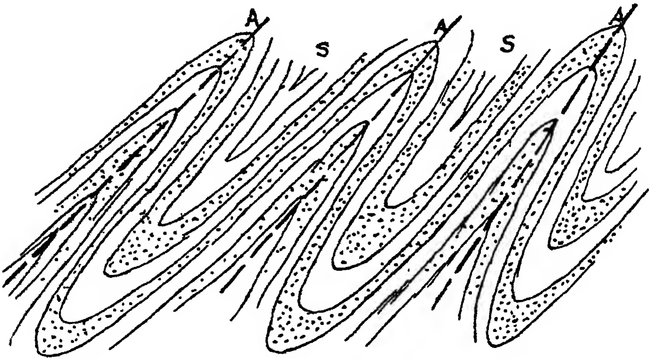


FIG. 27.—MUCH COMPRESSED INCLINED FOLDS; BEDS BECOMING THIN IN THE LIMBS AND THICKENING IN THE BENDS OR CORES.

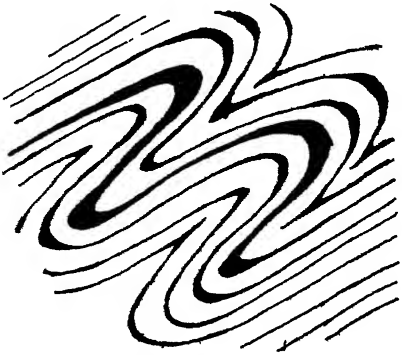
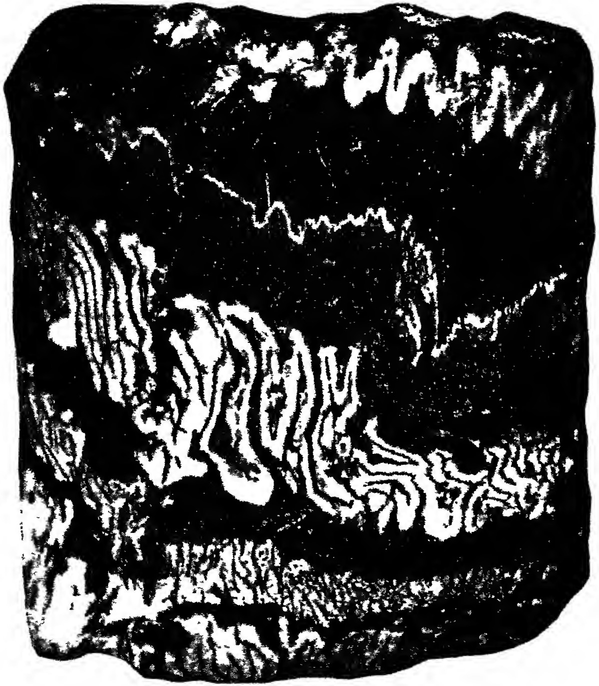


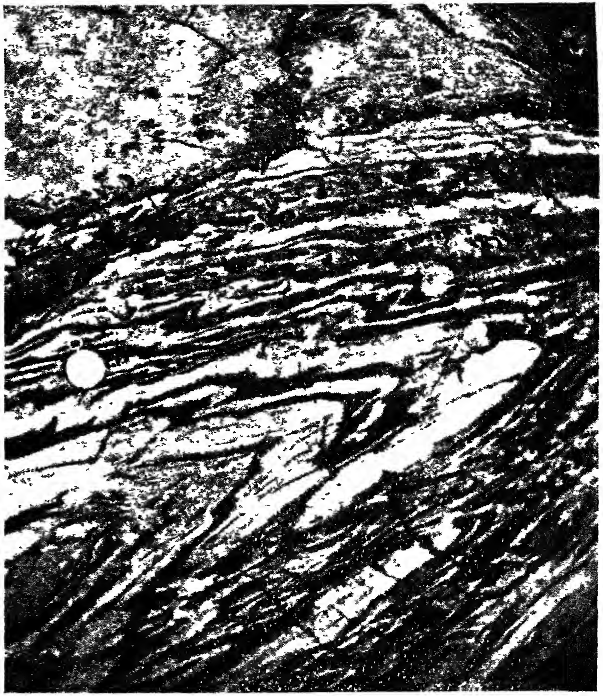
FIG. 28.—INCLINED FLEXURES; OVERFOLDS.

As the original crowns of the anticlines have invariably been removed, the truncated beds present the deceptive appearance of a great series of strata, all dipping at high angles in the same direction. In reality, however, as a glance at Fig. 30 will show, the same beds are again and again repeated, so that

PLATE XXXIII



1. CONTORTED ALPINE LIMESTONE (BANDED).
Nearly natural size.



2. CONTORTED LIMESTONE (BANDED), GLEN MOHR, GLEN TILT.
Photo by Sir J. S. Flett.

[*To face page* 138

the series is not by any means so thick as it might at first seem to be. This structure is very well developed in the Southern Uplands of Scotland. **Recumbent fold** (Fig. 31) is the name given to a flexure, the axial plane of which approaches horizontality. It is a structure of frequent occurrence in regions of highly convoluted strata, but is not so common as the ordinary overfold. Another structure, characteristic of the more highly disturbed portions of the earth's crust, is that shown in Fig. 32. In this structure two inclined synclines approach each other from opposite directions, while in the intervening space the strata are arched into a great anticline. The crown of the anticline has invariably disappeared, so

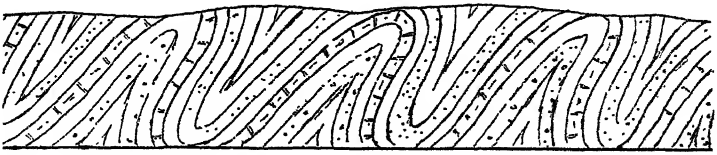


FIG. 29.—ISOCLINAL FOLDS.

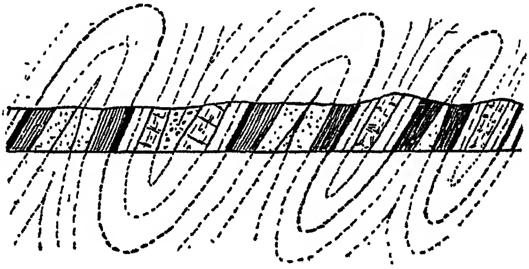


FIG. 30.—ISOCLINAL FOLDS, MUCH DENUDED.

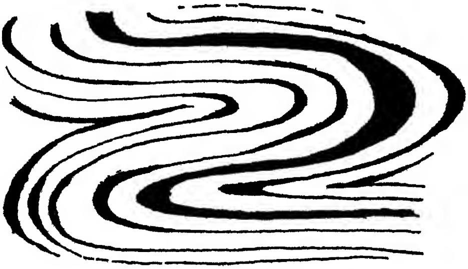


FIG. 31.—RECUMBENT FOLD.

that the truncated strata are seen to dip in from both sides towards the axial plane. Since the beds within the anticline are much compressed below while they open out above, they present the appearance known as **fan-shaped structure.**

All the several kinds of inclined folds described in the preceding paragraph occur in regions which have been subjected to some dominant movement of the crust—either of elevation or depression. When a broad zone has bulged up under lateral pressure to form a mountain range, we may have one great arch composed of numerous subordinate wrinkles or minor folds and flexures. A complex arch of this kind is termed an **Anticlinorium** (see Fig. 33). It is a fan-shaped structure on a large scale—the axial plane of the dominating central anticline being approximately vertical, while the axes of the subordinate lateral folds are inclined from either side towards the axial plane of the large central anticline (Fig. 33). The converse structure, resulting from the subsidence of a broad zone, is termed a **Synclinorium**

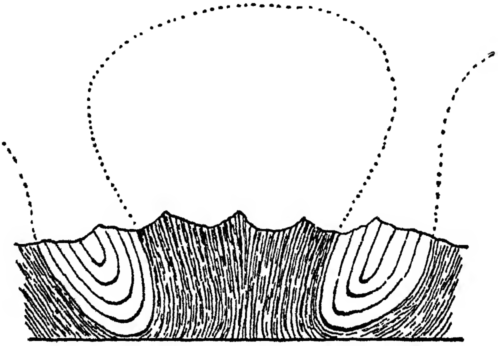


FIG. 32.—FAN-SHAPED STRUCTURE.

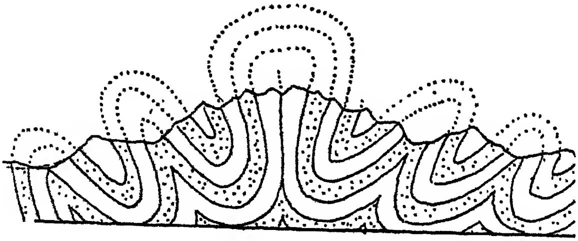


FIG. 33.—DIAGRAM OF AN ANTICLINORIUM.

(Fig. 34) which resembles an inverted anticlinorium. It may be pointed out, however, that the current usage of the term synclinorium is different from that of Dana, who first introduced it. By Dana it was applied to mountain ranges resulting from the compression of strata laid down in geosynclines. The diagrams, it must be understood, are quite schematic or ideal. The structures occur now and again among much folded strata, but probably no mountain-range is ever a complete anticlinorium, even when fan-shaped arrangement is more or less conspicuous.

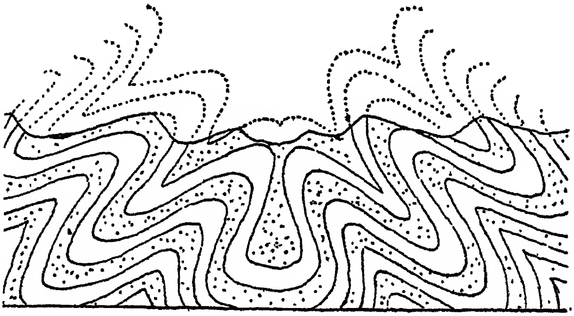


FIG. 34.—DIAGRAM OF A SYNCLINORIUM.

In most mountain-chains, indeed, the majority of the folds lean over in one direction as if they had experienced unilateral compression. If the portion of the crust subject to compression be more or less plastic or yielding, the folds, after reaching their full development, gradually fade away or die out in a series of gentle undulations, as in Fig. 35. Sometimes, however, a yielding portion of the crust is folded and thrust forward against a rigid or relatively stable area. When such is the case the folding terminates abruptly against the rigid area (Fig. 36), and not infrequently horizontal displacements take place and vast masses of rock are driven forward and piled upon the unyielding tract.

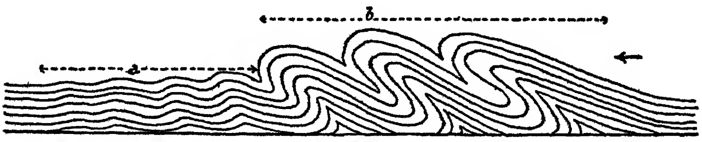


FIG. 35.—SIMPLE TYPE OF MOUNTAIN STRUCTURE.
a, Zone of least disturbance; *b*, Zone of greatest disturbance.

Contorted Strata.—When strata are so asymmetrically and abundantly folded that it becomes difficult or even impossible to trace out the individual flexures and crumplings—the whole forming an irregular complex of folds—they are said to be contorted (see Fig. 37; and Plates XXXII., XXXIII.). Such contorted rocks are frequently associated with the several kinds of inclined folds described in the preceding section. In all highly folded and corrugated strata the rocks have obviously been subjected to great compression. This is seen in the peculiar thinning and thickening undergone by the strata—the beds becoming attenuated in the limbs of the folds and swelling out again in the cores of the arches and troughs (see Fig. 27; and Plates XXXII., XXXIII.). It would seem, in fact, as if, under compression, the solid rocks had been compelled to yield and to behave like plastic bodies. The evidence of such shearing and flowing is conspicuous not only in the larger folds but in the smallest crumplings visible to the naked eye. Indeed, when the rocks are sliced and examined under the microscope they continue to show precisely the same structures. It is thus no exaggeration to say that folds vary in dimensions from great flexures measuring hundreds

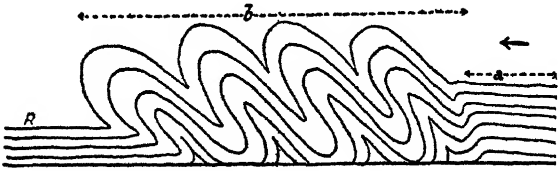


Fig. 36.—Simple Type of Mountain Structure.

a, Zone of least disturbance; *b*, Zone of greatest disturbance; *R*, Rigid or undisturbed area.

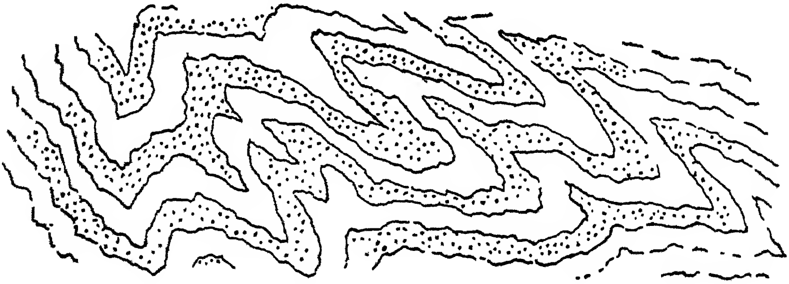


Fig. 37.—Contorted Folds.

of yards across, down to puckerings and crumplings so minute that they only become visible under the microscope (see Plate LVIII. 1, 2).

If in the case of contorted strata the individual beds and their subordinate laminæ have become distorted, it is not surprising that their individual constituents should similarly yield evidence of compression. Thus the rounded stones of a conglomerate (Plate LVIII. 3) are often flattened against each other and drawn out into elliptical or lenticular forms, while fossils are frequently distorted in like manner. This process of deformation has often proceeded so far as to result in the more or less complete alteration of the rocks, the original characters being either much obscured or even entirely obliterated. But the further consideration of such changes must be deferred until we come to discuss the phenomena of slaty cleavage and metamorphism.

Great Crustal Flexures.—The flexures and folds already described cannot possibly affect the whole thickness of the earth's crust, but are confined to the supercrust or external crustal shell. We do not know how thick the crust may be, but not improbably it is many miles, and therefore much too thick to be so abruptly flexed, folded, and contorted throughout as the supercrust. Nevertheless, it is subject to great upward and downward movements. These movements may affect areas many thousand square miles in extent, the resulting flexures being known as **Geanticlines** and **Geosynclines** respectively. Thus a geosyncline is simply a great depression of the crust, while a geanticline is the converse—a general bulging upwards of an extensive region. The flexures in either case are of low angle and quite independent of the geological structure or rock-arrangements of the supercrust and, therefore, they must not be confounded with ordinary anticlines and synclines.

CHAPTER X

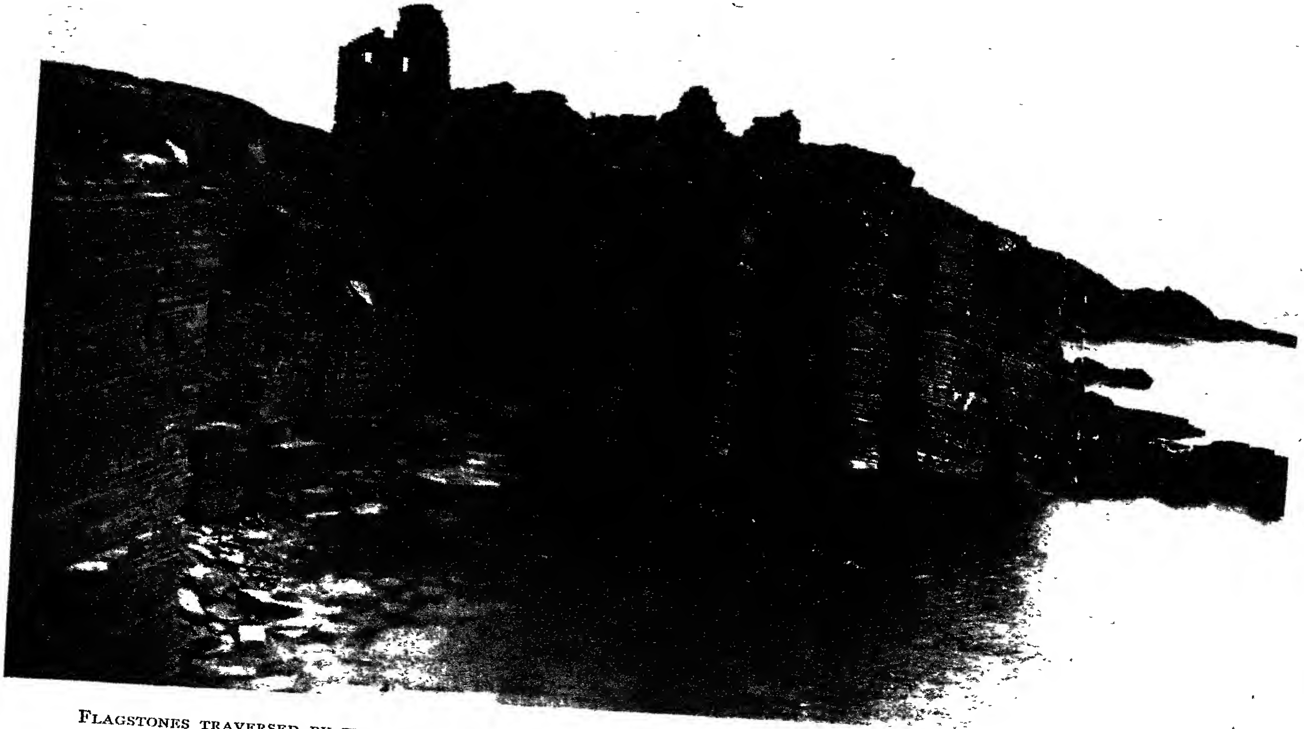
JOINTS

Joints, Close and Gaping. Joints in Bedded Rocks—Master-joints, Dip- and Strike-joints. Joints in Igneous Rocks—in Granitoid Rocks, Prismatic Joints. Joints in Schistose Rocks. Slickensides. Origin of Joints—Contraction, Expansion, Crustal Movements.

JOINTS are superinduced divisional planes which traverse rocks in different directions and at various angles, so as to allow of their ready separation into larger and smaller blocks and fragments of regular or irregular shape. The faces of a joint are generally smooth and flat, but in certain cases (as in many crystalline igneous rocks) they are often somewhat curved. In fresh, unweathered rocks, joints are usually inconspicuous, the faces being sometimes in such close apposition that the fissure can hardly be detected. The presence of even the closest joints, however, is often betrayed by the alteration of the rock induced by percolating water—the degree of alteration naturally depending to a large extent upon the character of the rock. In the case of red sandstone, for example, the position of the joints is frequently indicated by more or less vertical lines and bands of bleached rock. In limestone, again, the joints tend to gape, as might have been expected from the ease with which that rock is dissolved by acidulated water. The faces of joints are frequently coated with a pellicle of brown or yellow iron-oxide; or with other depositions from aqueous solution, such as calcite, barytes, quartz, chalcedony, etc. Gaping joints are in like manner often filled with similar products—and are then described as veins, which may vary in width from less than an inch up to many feet. The phenomena of mineral veins, however, will be considered in a later chapter, under the general head of Lodes.

As a rule, the more important joints in solidified rocks of all kinds tend to be somewhat open, or, at all events, are most readily recognised at and for some distance down from the surface, becoming less and less

PLATE XXXIV



Flagstones traversed by two sets of Joints at right angles to each other.—Buchollie Castle, Caithness.

Photo by H.M. Geological Survey.

[*To face page* 144

conspicuous as they are followed to greater depths. It is impossible to doubt that these appearances are due to epigene action, the influence of which must gradually die out downwards. The opening of the joints in readily soluble rocks like limestone may be safely attributed to percolating water; but, in the case of relatively insoluble rocks the fissures can hardly have been opened by the same means, and are more likely to have been widened by changes of temperature. In temperate latitudes, however, diurnal and seasonal changes of temperature do not affect rocks beyond a few feet from the surface, and can scarcely account, therefore, for the phenomena referred to. We must remember, however, that during relatively recent geological times the present temperate latitudes of Europe and North America experienced certain remarkable climatic vicissitudes—having sometimes been subjected for lengthy periods to the rigours of an arctic climate, while at other times the conditions would seem to have been more genial than they are now. Under such alternations of cold and heat the rocks could hardly fail to have been affected to a much greater depth than is possible at present. We know that in high latitudes the ground is permanently frozen to a depth of over a hundred feet, and that the heat of summer suffices to thaw only a thin superficial stratum. Were glacial conditions, therefore, again to supervene in temperate latitudes, we cannot doubt that, with increasing cold, frost would penetrate ever deeper and deeper—the rocks contracting and all moisture becoming frozen to depths approximating those reached by frost in sub-arctic regions. With the gradual return of genial conditions thawing would ensue until no part of the ground remained permanently frozen. To this process of alternate freezing and thawing, repeated again and again throughout the long glacial cycle, we ought perhaps to assign the opening up of joints at considerable depths from the earth's surface.

Joints in Bedded Rocks.—Sedimentary rocks are usually traversed by two sets of joints, perpendicular to the planes of bedding, and intersecting each other at approximately right angles. Not infrequently these joints run roughly parallel for long distances, and when they do so they are known as *Master-joints.* Usually, however, it is impossible to follow individual joints very far, and the parallelism of a series is only approximate, for often enough one joint runs into another. In some cases, indeed, individual joints seem to die out in a few yards, and to be succeeded after a longer or shorter interval by one or more following the same general direction. The width of rock between adjacent joints, belonging to the same parallel series, is very variable. In some cases it may be many feet or even yards; in other cases it may be considerably less than a foot. In certain thin-bedded strata, for example, so closely set are the joints that the rock breaks up readily into small cubes and parallelopipeds. In addition to the more or less regularly intersecting main joints, numerous subordinate joints may traverse a rock in many different directions; and when such is the case the system of main joints becomes obscured or unrecognisable—the irregularly fissured rock breaking up into a rubble of larger and smaller angular fragments (Plates XXXIV., LXVIII., LXIX.).

When bedded rocks are inclined, the intersecting main joints are known as *dip-joints* and *strike-joints* respectively—the former running in the direction of the dip or inclination of the beds, while the latter cross these at approximately right angles. Strike-joints are usually more pronounced than dip-joints. To this rule, however, there are many exceptions—sometimes the latter being more conspicuous than the former, while not infrequently the one set is hardly better developed than the other.

The joints that traverse a succession of alternating strata of limestone, shale, sandstone, etc., are often interrupted and sharply shifted to the side as they pass from one bed to another. Often, indeed, certain beds in a series are more regularly divided than the immediately overlying and underlying strata, the jointing of which may be very irregular and more abundant or less so than that of the intermediate strata. In such cases the divisional planes of the several beds appear to be more or less independent.

While regular jointing may be met with in all kinds of derivative rocks, it is best displayed, as a rule, in fine-grained deposits of homogeneous composition, as in limestones, freestones, flagstones, coal, etc. Common household coal, for example, is divided by three sets of planes disposed at right angles to each other: namely, (*a*) planes of bedding, with a dull sooty surface, and (*b*) and (*c*) joint-planes with bright surfaces. One set of joints (*b*) runs in the direction of the inclination or dip of the bed, and is termed by miners the "end of the coal," the other set (*c*) traverses the bed at right angles to the "end," and is known as the "face or cleat of the coal." The "face," therefore, coincides with the *strike* of the strata. In a coal-mine cross-galleries are driven in the direction of the "end" (*i.e.* with the dip or inclination of the strata), while the working-galleries are driven along the "face" (*i.e.* the strike) and they necessarily follow, therefore, a level-course. So long as the inclination of the strata remains constant in direction, the working-galleries must follow a straight line at right angles to the dip, but with any change in the direction of the latter there will necessarily be a corresponding change in the direction of the "level-course."

Excellent examples of regular jointing are exhibited by the thick Carboniferous Limestones of Ireland and England—the main or master-joints crossing each other nearly at right angles, and preserving their direction for long distances. The Old Red Sandstone strata of N.E.

Scotland, which are so finely displayed in numerous coast sections, afford equally good illustrations of the same structure (Plate XXXIV.).

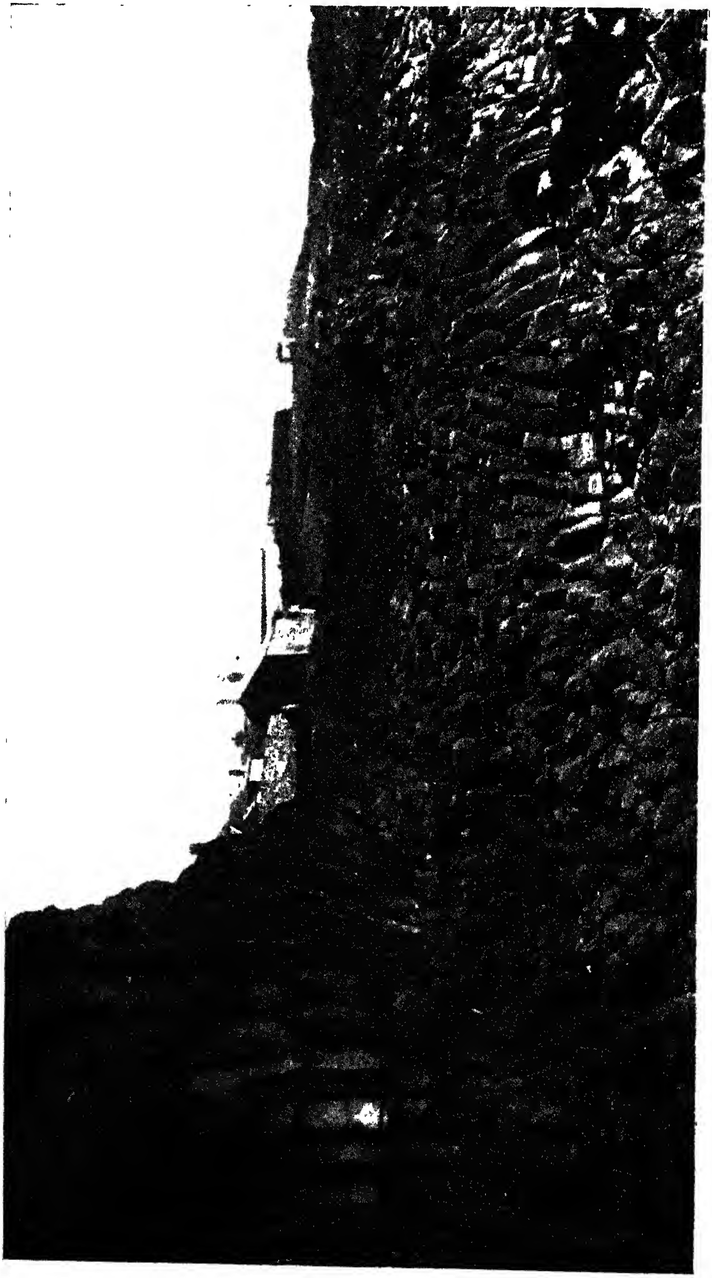
Joints in Igneous Rocks are seldom as regularly arranged as those of sedimentary strata; indeed, they are frequently so very irregular that no system or arrangement can be recognised. In other cases, however, the division-planes show a modified regularity, following determinate directions like the master-joints described above; while in yet other cases they are so symmetrically disposed as to confer a prismatic columnar structure on the rock they divide.

The joints in granite are often wonderfully regular—two sets of vertical or steeply inclined division-planes intersecting at various angles, which often do not depart widely from right angles. The rock thus tends to be divided into columnar masses that vary in shape according to the character of the joints (which may be straight or curved) and the angle at which they intersect. Sometimes the joints are widely separated so that large monoliths can be obtained; at other times they are so closely set that the rock breaks up into a rubble of small fragments. The main vertical joints are often accompanied by minor irregular joints the presence of which necessarily prevents the extraction of large blocks. In addition to its vertical division-planes granite often exhibits a set of cross-joints, arranged at approximately right angles to the others. These cross-joints may be horizontal or inclined, and often give the rock a kind of bedded appearance, at least towards the surface (Plates XXXVIII., LXVIII.). They are seldom, however, so even as planes of bedding. Usually they are somewhat undulating, and run into each other so as to divide the rock between the vertical joints into a series of lenticular and interosculating layers or sheets. This structure when viewed from a little distance sometimes simulates the appearance of false-bedding. These curious joints are most conspicuous towards the surface, where they are often only a few inches apart. The width between them, however, increases with the depth, while at the same time the joints become closer and more discontinuous, until at last they disappear. The joints in question are thus obviously related to the surface and this relation is rendered still more evident by the fact that they are always approximately parallel to the surface. Thus, when the ground is level the cross-joints are horizontal; but when it is inclined the joints have a similar dip. In a broad, dome-shaped mountain of granite, for example, the rock often appears to consist of a series of rudely concentric shells, which at the summit are horizontal, but from thence dip outwards in all directions, coinciding roughly with the average fall of the ground.

Cross-joints of the kind described above are not confined to granite, but occur in other massive eruptive rocks. They have been observed, for example, in some syenite sand quartz-porphyries (Plate XXXIX.), but are seldom so well developed. [Even homogeneous sedimentary rocks, such as limestone and freestone, now and again exhibit a similar structure which cannot be mistaken for true bedding.]

The columnar structure of granitoid rocks due to jointing is by no means so well developed as that of certain other igneous rocks. Many basalts, for example, are jointed so symmetrically that the rock looks like an organised aggregate of prismatic columns (see Plate XXXV.). When this structure is fully developed, as in the well-known rocks of Fingal's Cave and the Giant's Causeway, the columns tend to assume hexagonal forms. But although six-sided columns are common enough, yet the faces of the prisms are seldom equally developed, while many columns may show fewer or more faces than six, so that trigonal, tetragonal, pentagonal, and polygonal forms are often associated. This prismatic structure is always developed at right angles to the planes of cooling. Hence, when the rock is in a horizontal position—the upper and under surfaces being planes of cooling—the columns are vertical. When, on the other hand, the molten rock has cooled and solidified in a vertical fissure, the walls of this fissure have formed the cooling-planes, and the columns are therefore horizontal. In the case of intrusive sills or sheets of basalt, the columns sometimes extend continuously from one cooling-plane to another; in dyke-like intrusions, however, they are usually not continuous but separated halfway by an irregular line. Now and again, indeed, small dykes and veins of basalt are wholly composed of successive thin belts or layers of prisms—the prismatic layers being separated by a series of roughly parallel fissures (see Figs. 80, 81, p. 202). In lavaform rocks the columnar structure seems likewise to be related to planes of cooling—the columns being vertical or inclined according as the rock has cooled upon a horizontal or an inclined surface. Not infrequently, both in lavaform and intrusive rocks, the columns are curved; and in most

PLATE XXXV



COLUMNAR BASALT, PETTYCUR, KINGHORN, FIFE.

Photo by H.M. Geological Survey.

[*To face page* 149

cases, whether curved or straight, they are usually intersected at more or less regular intervals by transverse or cross-joints, which in some few cases show a ball-and-socket arrangement —the convex surface of one segment fitting into the concave surface of the next overlying or underlying block. For it is to be noted that the convex surfaces of the segments in adjacent columns, or even in one and the same column, do not always point in the same direction.

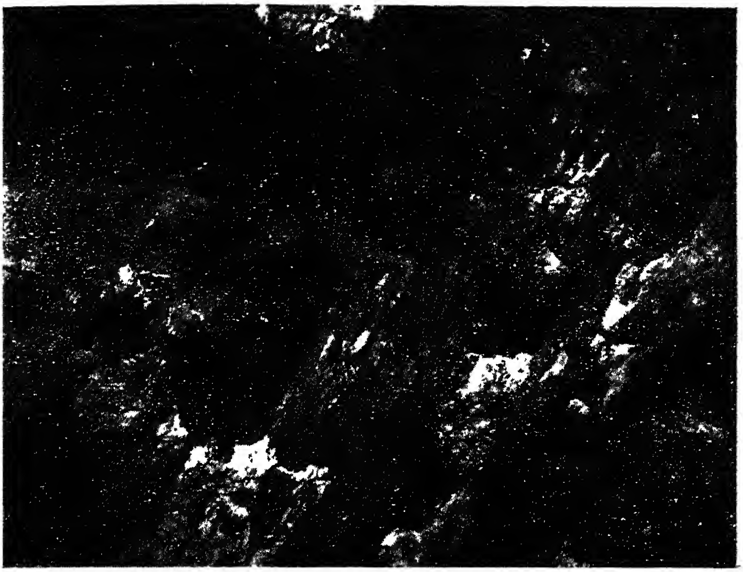
The columns or pillars vary much in size. In some thin dykes of basalt they may be less than an inch in diameter and only a few inches in length, while in thick sheets and lava-flows they may attain a thickness of 1 or 2 feet and a length of 200 feet or more. Prismatic jointing, although as a rule best developed in fine-grained basic igneous rocks, is by no means confined to these, for it is often well developed in andesites, quartz-porphyries, and now and again in obsidian. [Neither is the structure in question confined to igneous rocks. Even sandstone and coal occasionally exhibit a superinduced prismatic structure. In such cases the rocks have been influenced by the presence of intrusive igneous masses. Excellent examples occur in the Scottish coalfields, where whole beds of coal have been converted into a kind of prismatic coke; while at and near their contact with eruptive rock the sandstones often acquire a kind of rude columnar structure.]

Joints in Schistose Rocks.—As schistose or foliated rocks differ much in composition and structure, they might have been expected to show considerable variety in the character of their jointing. Those of them in which the foliated structure is well developed are occasionally divided by vertical or steeply inclined joints, but these are very rarely arranged symmetrically, and no system of intersecting joints like those of sedimentary strata can be detected. Now and again, however, granitoid gneiss is crossed by division-planes which have a general resemblance to the joints of granite. But, as a rule, the jointing of schistose rocks is irregular and capricious.

Slickensides (Plate XXXVI.).—The surfaces of joints in all kinds of rock are often smoothed and marked by parallel ruts and striæ, as if the opposite rock-faces had been ground and rubbed against each other. These *slickensides*, as they are termed, are frequently coated with a skin of mineral matter, which naturally shows a cast of the opposite joint-face, and thus has the appearance of having itself been smoothed and striated. In opening up a joint occupied by a thin vein of mineral matter, it is often possible to detach complete segments of the vein, which yield a cast of both joint-faces. While slickensides are not confined to any particular areas, they yet tend to be most abundantly developed in regions where considerable crustal movement or rock-displacement has taken place. They often occur, for example, in the joints of rocks near lines of fracture and dislocation of the crust, and, as we shall learn presently, the walls or faces of such dislocations themselves frequently exhibit the same smoothed and striated appearance.

Origin of Joints.—No one cause suffices to explain all the phenomena of joints. In many cases we can hardly doubt that these superinduced division-planes are simply fissures of retreat, formed during the consolidation and solidification of the rocks in which they occur. Some joints, again, are of such a character as to show that considerable force was required for their production, and these are suggestive, therefore, of crustal movements of some kind. The precise origin of others, however, is still obscure. The more obvious causes which have led to the jointed structure of rocks may be considered under the headings of *Contraction*, *Expansion*, and *Crustal Movements*.

CONTRACTION. Any moist and plastic rock, such as clay, necessarily contracts while drying, and in this way becomes more or less abundantly cracked or fissured. Possibly this may be the origin of many of the minor or subordinate irregular joints of sedimentary strata, but it does not account for the vertical intersecting joints which are so characteristic of these rocks. The passage from the non-crystalline to the crystalline condition also involves contraction, and thus we may suppose that the crystallisation of certain chemically formed deposits may have been the cause of their jointed structure. To the same cause must undoubtedly be attributed most of the division-planes occurring in crystalline igneous rocks, such as the vertical joints in granite and the prismatic jointing of basalt and other eruptive rocks. The cross-joints of granite, however, cannot be accounted for in this way. The simple fact that they are present only in the upper part of a rock-mass and disappear entirely at lower levels suffices to show that they have not the same origin as the vertical joints between which they have been developed. It is otherwise with the cross-joints of basalt, etc., which appear to be of the same nature as the prismatic joints with which they are associated—fissures of retreat, due to the contraction of the rock in cooling. The peculiar manner in which basalt and many other igneous rocks weather is somewhat suggestive. Prismatic columns which have been long exposed often lose their angular form, the individual segments or blocks assuming a spheroidal shape, so that the rock appears as if built up of vertical rows of globular ball-like or cheese-like bodies. Each of these spheroids exfoliates in successive concentric shells—a fraction of an inch in thickness—and the external ones may be readily detached by the hammer. The shells, however, become



1. SLICKENSIDES, PARTLY COATED WITH MINERAL MATTER (WHITE).

2. SLICKENSIDES, NOT COATED.

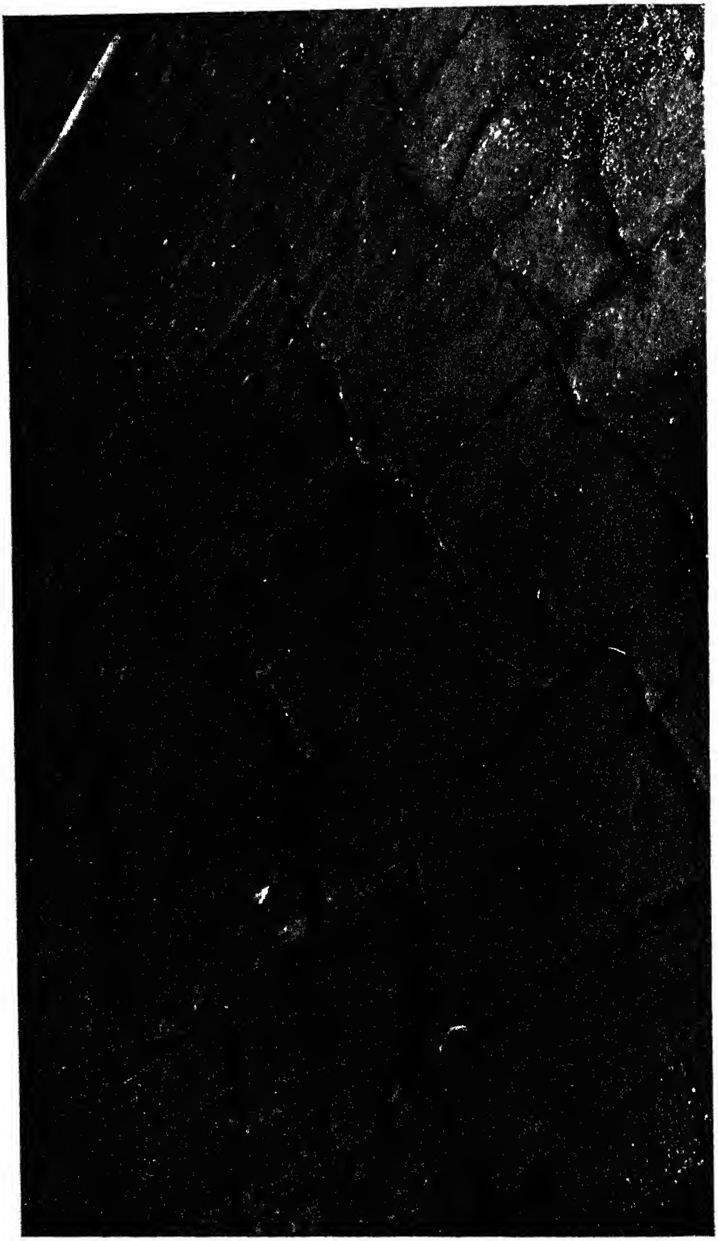
more adherent and less conspicuous as we penetrate the rock until they cease to appear. This peculiar kind of weathering is not confined to rocks which show a prismatic structure, being met with not only in non-columnar basalt but in many other igneous rocks, as in some pitchstones, granites, diorites, porphyries, etc. The weathering often proceeds so far that the exfoliating crusts break down into a kind of earthy or sandy grit, till nothing of the original rock may be left save a few scattered balls or cores. It is supposed that the shell-like structure betrayed by weathering is really original, the centre of each spheroid having been a centre of contraction. So long as the rock is fresh the structure remains invisible, and only becomes apparent when weathering supervenes. This is a plausible or even probable explanation of the phenomena, but it does not quite carry conviction. The perlitic structure of glassy rocks (which is due to the presence of numerous minute and roughly concentric cracks produced during cooling and contraction) has been cited as an example on a small scale of that spheroidal structure of basalt, etc., which is only revealed by weathering. All one can say is, that nothing comparable to perlitic structure has ever been detected by the microscope in those crystalline rocks which weather spheroidally—there is nothing in the microscopic appearance of basalt, diorite, etc., that would lead one to expect that such rocks should exfoliate in successive concentric shells. While, therefore, we need have no doubt as to the vertical and cross-jointing of basalt, etc., being due to contraction, the origin of the shell-like structure exhibited by weathering and decomposing rocks is still an open question.

EXPANSION. Rocks of all kinds when subjected to heat will necessarily expand, and when cooling will contract. As a result they become rent and fissured. Excellent examples are seen in the Scottish coalfields. Thus beds of common coal, subjected to the heat of molten rock erupted in their immediate neighbourhood, have been converted into prismatic coke. In such cases the coal having been subjected to destructive distillation has, of course, lost some of its constituents. Even siliceous sandstones and argillaceous shales invaded by eruptive rock-masses often acquire a rudely columnar structure. But sun-heat is a much more general cause of expansion. This is probably effective in all latitudes, but naturally enough its results are best studied in dry tropical and subtropical regions. In temperate and higher latitudes, the effect of insolation is obscured or entirely concealed by the much more energetic action of frost and other epigene agents. In warm and relatively rainless regions the rocks are heated up during the day to a high temperature—consequently their superficial portions expand to such an extent that they often become detached, and bulge up from the underlying rock of which they form a part. In this way igneous rocks sometimes acquire a superficial flaggy structure. When night falls rapid radiation ensues and the rocks quickly contract, so that the superficial portions tend to break up more or less rapidly. In the case of fine-grained homogeneous rocks, the highly heated surface often peels away in thin sheets which curl up, and are readily removed by the wind. The flags produced by desquamation naturally coincide with the surface, so that they may be curved, inclined, or horizontal according as the rock-surface is rounded, sloping, or level. Their direction is, therefore, independent of any internal rock-structure.

The cross-joints of granite may, in like manner, owe their origin to epigene action. The phenomena connected with them seem at least to point to that conclusion. They are always approximately parallel with the surface, are most numerous and strongly marked in the superficial part of the rock, and as they are followed downwards, appear at longer and longer intervals, becoming, at the same time, more interrupted in their course and less conspicuous, until finally they disappear. Further, it may be noted that the " grain " or " rift " of the granite—*i.e.* the direction in which the rock splits or breaks most readily—is parallel with the cross-joints. Not only so, but, like the latter, it is most marked near the surface, and gradually dies out downwards as they disappear. Now there is no apparent petrographical structure to account for this " grain," and its coincidence with the cross-jointing. The rock consists throughout of a heterogeneous pell-mell aggregate of minerals. It is otherwise with sedimentary rocks, the " grain " or " rift " of which naturally coincides with planes of deposition, just as the " grain " of a schistose rock coincides with planes of foliation. The grain of some crystalline igneous rocks is due, likewise, to a roughly parallel arrangement of their constituent minerals, as in the case of phonolite, which, owing to the orientation of its dominant mineral, often cleaves more or less readily into parallel slabs and flags. So again, many lavaform rocks, and even occasionally intrusive sheets or sills and dykes, have a tendency to split most readily in the direction of flow. In most cases the " grain " is determined by the more or less obvious parallel arrangement of the rock-ingredients—a rock dividing most readily when the orientation is best developed. When such arrangement is very obscure or not at all visible, as in heavy lavas and sills, the coincidence of the " grain " with the direction of flow seems, nevertheless, to show that the " grain " is an original structure. No such structures, however, occur in normal granite—the grain of which certainly does not depend on the alignment of its constituents. Neither does it bear any relation to possible movements of the original molten mass, nor to the vertical joints or fissures of retreat produced by contraction. It has apparently been superinduced in granite by epigene action—and may perhaps be due to the expansion and contraction induced by seasonal and secular changes of temperature. This inference gains support from the fact that cross-jointing and coincident " grain," similar to those of granite, have been observed in other kinds of eruptive rock. Cross-jointing has even been superinduced in the upper parts of fine-grained homogeneous aqueous rocks, where consolidation from a state of igneous fusion is, of course, excluded. But if such structures can be superinduced by epigene action, we may be led to suspect that the exfoliating spheroids of weathered basalt, etc., are likewise independent of any original structure due to contraction while the rock was cooling—that, in short, the concentric shells are solely the result of changes of temperature and of weathering generally.

CRUSTAL MOVEMENTS. While it may be admitted that the tension brought about by the causes already considered must have induced the formation of fissures in many kinds of rock, there is yet a large class of joints which cannot be thus explained. The regular intersecting systems of master-joints in sedimentary strata are suggestive rather of powerful

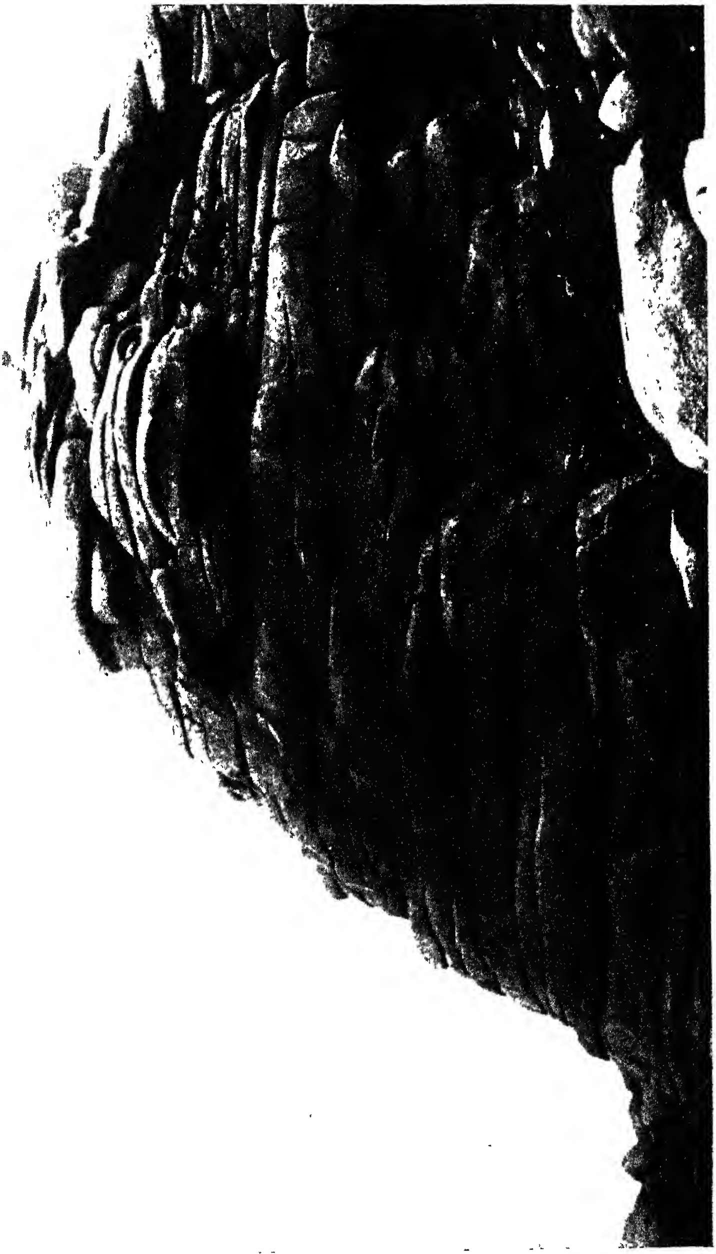
PLATE XXXVII



Ripple-marked Sandstone traversed by Joints, near Kinghorn, Fife.

Photo by H.M. Geological Survey.

PLATE XXXVIII



Tabular Joints in Granite, Summit of Goatfell, Arran.

Photo by H.M. Geological Survey.

[*Between pages* 152 *and* 153

mechanical stress and strain. The strata have been cut through as smoothly as if they had been severed by a knife; and this is true not only of homogeneous rocks, such as limestone, but of heterogeneous aggregates like conglomerate. In the latter rock the superinduced division-planes pass without interruption through stones and matrix alike, even although the stones may consist of much harder and tougher material than the matrix in which they are embedded. Had such joints been the result of contraction only, the stones would simply have been pulled out of the matrix on one side of a fissure and left projecting from the surface of the other. The general opinion is that joints of this kind are the result of crustal movements. It is not difficult to conceive how strata, subject to compression and tension during such movements, should have cracked and become fissured. We seem thus to get a ready explanation of the strike-joints, for it is along the axes of folds that strata would be subject to the greatest compression and tension. It seems also reasonable to infer that dip-joints might have originated at the same time. Various interesting experiments by the famous French geologist, A. Daubrée, tend to show that two series of intersecting joints might be expected to result from powerful crustal movements. Daubrée experimented upon long rectangular plates composed of various substances, and demonstrated that these, when subjected to the strain of torsion, were traversed by two sets of approximately parallel cracks, one system crossing the other at angles of 70° to 90°, and thus closely simulating the intersecting master-joints of stratified rocks.

Mr W. O. Crosby has suggested another explanation of the normal intersecting joints so characteristic of bedded rocks. He thinks that these are probably due to earthquake action. The fractures produced by vibratory movements of the earth's crust he shows must be plane, parallel, intersecting, and normally vertical, thus possessing all the characteristics of master-joints. Mr Crosby thus appeals to a *vera causa*, but his theory does not exclude that which would attribute dip- and strike-joints to folding. It affords a better explanation, however, of the vertical intersecting joints of horizontal strata, which can hardly be accounted for by torsion. Undisturbed horizontal strata, covering wide regions, are often as regularly jointed as strata which have been folded. In such cases, therefore, we may suppose the jointing has most probably resulted from the passage of earthwaves through the rocks, the alternate compression and tension having been sufficient to produce fissuring. As there is possibly no part of the earth's crust which has not experienced earthquake shocks and vibrations, such crustal movements may have played a more important rôle in the formation of joints than might be suspected. The great crustal movements which resulted in the buckling up and folding of strata in gigantic mountain-chains, must often have induced severe earthquakes, caused by the sudden yielding of rock-masses to tension; but the fissuring and shattering due to the passage of such vibrations or waves of elastic compression could not now be distinguished from the ordinary effects of folding and torsion.

CHAPTER XI

FAULTS OR DISLOCATIONS

Normal Faults. Dip-faults and Strike-faults—their effect upon Outcrops. Oblique Faults. Systems of Faults. Step-faults. Trough- and Ridge-faults. Shifting of Faults. Reversed Faults. Transcurrent Faults. Origin of Faults.

HAVING now learned that rocks of all kinds are more or less fissured, and that no small proportion of the joints by which they are thus traversed appear to owe their origin to crustal movements, we must next make the acquaintance of fissures of another kind, known as Faults or Dislocations. These are doubtless due likewise to crustal movements, but they differ from joints in being not mere cracks or rents, but fissures of displacement. The rocks on one side of a fault are thus abruptly truncated and brought against younger or older rocks on the other side. Three types of faults are recognised, namely, (a) *Normal Faults*, (b) *Reversed Faults*, and (c) *Transcurrent Faults.*

NORMAL FAULTS. These dislocations are rarely, if ever, quite vertical, although in natural exposures they sometimes appear to be so. But when they are followed downwards, as in mining operations, they are invariably found to be inclined, the degree of inclination varying, it may be, from point to point, so that in places they occasionally show verticality. The general inclination of a fault from the vertical is termed the **hade**, and this, in the case of normal faults, is always in the direction of the downthrow. The degree of deviation from the vertical is quite indeterminate; but, as a general rule, the larger are more steeply inclined than the smaller faults. But to this rule many exceptions occur. The amount of vertical displacement is known as the **throw** * of a fault, and is measured by protracting a line in a horizontal direction

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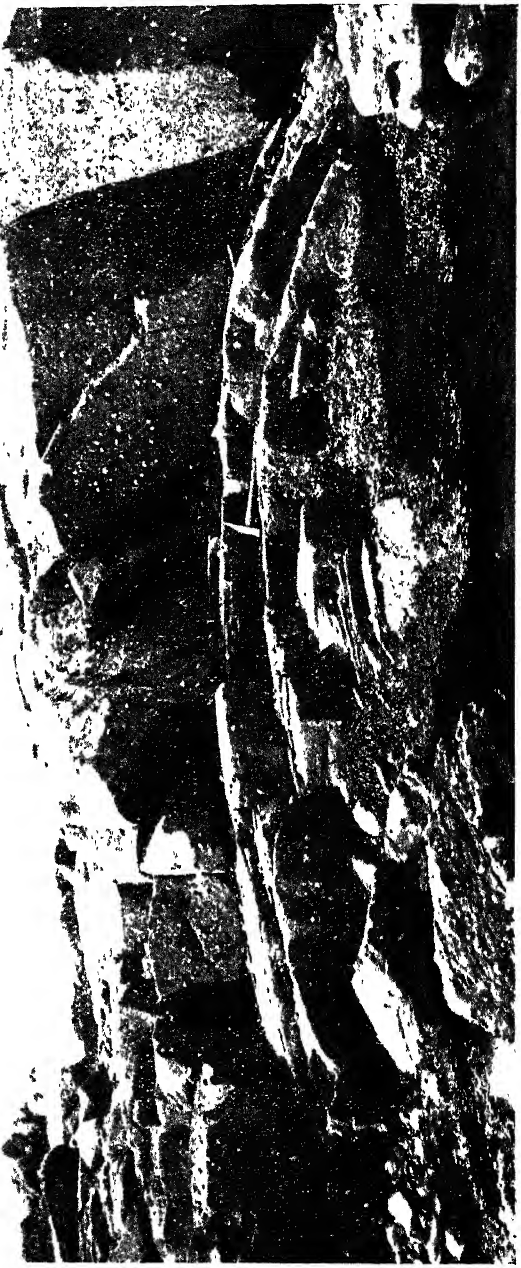
* The amount of displacement varies indefinitely. Some faults are mere slips of a few feet or inches; others are downthrows of several thousand yards. Between these extremes all gradations are met with.

PLATE XXXIX



Curved Joints in Felsite, Blackwater Foot, Arran.

Photo by H.M. Geological Survey

[*To face page* 155

(as in Fig. 38), across the fault from the truncated end of some particular bed (a) until a perpendicular (x—a^2) dropped from the protracted line can reach the other end of the selected stratum on the opposite side of the fault. Miners seldom use the term *fault*, but speak of *downthrows* or *downcasts*, and *upthrows* or *upcasts*, according to the direction in which they are working. Thus the faults (F^1, F^2) shown in Fig. 38 would be described as downcasts or downthrows if they were encountered by a miner working in the direction from A to a, or from a to A, but he would speak of them as upcasts or upthrows, if he approached them from the direction of C to a^2, or from B to a^2.

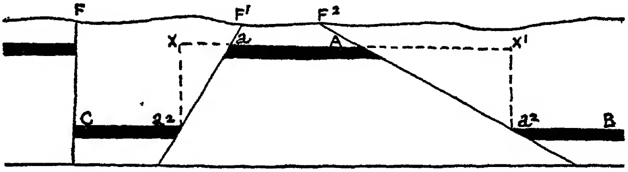


FIG. 38.—NORMAL FAULTS IN HORIZONTAL STRATA.

It is obvious that in Fig. 38, representing faulted horizontal strata, the amount of throw is equal to the thickness of the beds lying between x—a^2 and x^1—a^2; but this is not so in the case of inclined strata. In Fig. 39, for example, the amount of vertical displacement (a—x) is in excess of the thickness of the strata measured as in the preceding illustration (Fig. 38) at right angles to the planes of bedding (a^1—a^2).

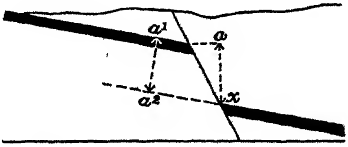


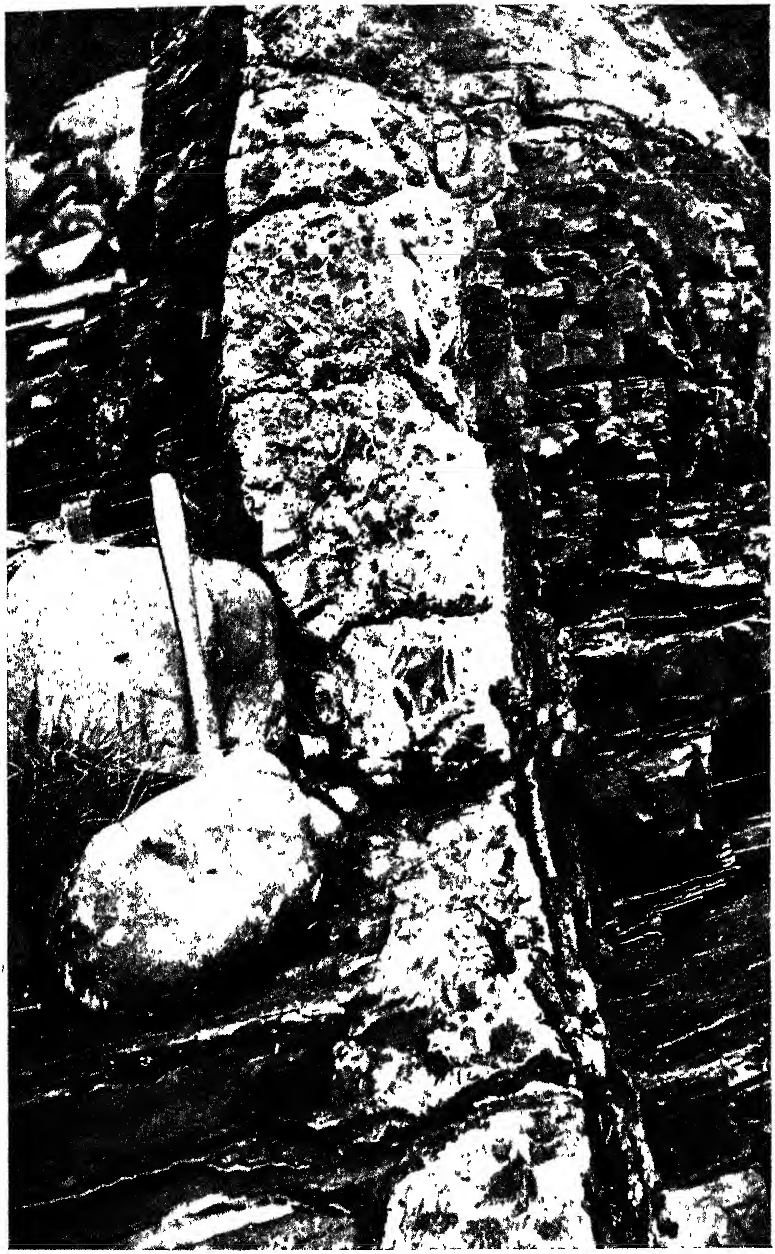
FIG. 39.

Strata cut across by an inclined fault are not only dropped to a lower level on the downthrow side, but the fault has the effect of producing a lateral displacement or **heave**—the amount of which is determined by the hade and the throw. For example, the truncated end of the coal-seam a (Fig. 38) is removed laterally by F^1 from its disconnected continuation a^2 by the distance a—x; but it is obvious that this distance would be increased if the amount of downthrow were augmented. Again, with the more gently inclined fault (F^2), the lateral displacement or *heave* is considerably increased.

In the case of the vertical fault (F) there is, of course, no heave or lateral displacement. The inclination of faults, therefore, is of great importance in a coalfield, for the further the hade deviates from the vertical the wider will be the extent of "barren ground" between the two ends of a dislocated coal-seam.

The faults shown in the diagrams are straight lines, but in reality faults are not always or even often so smooth as they are here represented to be. Although the walls of a fault may be in close apposition, they are often separated either continuously or at irregular intervals by masses of jumbled and shattered rock-débris, known as **fault-rock** or **fault-breccia** (Plate XL.). In many cases, also, cavities occur along a line of dislocation, and these are often filled or partially filled with crystallised minerals, as will be shown more particularly when we come to consider the phenomena of lodes or metalliferous veins. The walls of a fault and the stones in a fault-breccia are frequently slickensided, and afford other evidence of friction and crushing—the rocks along one or both sides being sometimes comminuted or pulverised for some inches or even for many feet back from the dislocation. Phenomena of this kind occur chiefly in connection with the more powerful faults—those, namely, which have produced the greatest amount of vertical displacement. In the neighbourhood of such large faults the rocks are not only broken and jumbled, particularly on the downthrow side, but on the same side strata are frequently turned up more or less abruptly against the dislocation. On the high side of the fault there is usually less disturbance and distortion, although the rocks tend to be bent over as if they had been dragged downwards in the direction of displacement. The annexed sections (Figs. 40, 41) will suffice to illustrate these appearances.

As a general rule, normal faults are more or less closely related to the leading or dominant rock-foldings of the district in which they occur. Hence they can usually be described as **Dip-faults** and **Strike-faults,** in this respect recalling the systematic arrangement of the joints characteristic of sedimentary strata. It must not be supposed, however, that the coincidence of faults with dip and strike is always close. The most that can be said is that they trend approximately in those directions. Frequently, however, they traverse the rock-folds obliquely, just as joints do, and sometimes it is



FAULT-ROCK, RIVER GARRY, AT DALNACARDOCH, PERTHSHIRE.

Photo by H.M. Geological Survey.

[*To face page* 156

difficult to detect any system or arrangement among them. Nevertheless, the larger faults tend, on the whole, to coincide more or less closely with the geological structures referred to —a relation which can hardly be said to characterise the smaller or less important dislocations. In these and other respects, therefore, normal faults have many analogies with the joints of sedimentary accumulations.

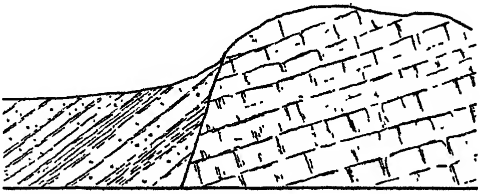


FIG. 40.—NORMAL FAULT, NOT ACCOMPANIED BY DISTORTION.

Dip-faults have a characteristic effect upon the outcrops of rocks, which they appear to shift. This is well seen when such a fault crosses an escarpment, the long line of which is suddenly interrupted and shifted forward or backward according to the position from which we view it. This advance or retreat of the outcrops along a line of dip-fault must not be confounded with the lateral displacement already referred to as the "heave" of a fault. It is the degree of inclination or "hade" and the amount of downthrow that determine the extent of lateral displacement, or "heave." A dip-fault, if vertical, produces no heave; but whether vertical or inclined, it never fails to cause an apparent horizontal shift of the outcrops—either forward or backward—according to the direction of downthrow. This apparent advance or retreat of faulted outcrops is greatest when the angle of dip is low, diminishes in proportion as the dip augments, and ceases altogether when the beds are vertical. The shifting, however, is not the result of any horizontal movement along the line of dislocation, but is simply the effect produced by denudation, as a glance at the models in Fig. 42 will show. Let A represent

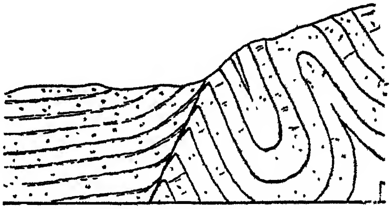


FIG. 41.—NORMAL FAULT, ACCOMPANIED BY DISTORTION.

a block of strata dipping in one determinate direction. A dislocation, we shall suppose, takes place along the interrupted line *f f*. In B we have the same model showing the vertical displacement effected. A line dropped from the truncated end of the bed a' to its disconnected continuation a^2 is a perpendicular—in other words, the fault is a vertical displacement. Now let us suppose that the surface is cut even by denudation along the line *s s*. The portion above this line we remove, and we have in C a ground-plan of the new surface thus produced. It now becomes evident that the horizontal shift is only apparent, and is simply the result of the removal of strata from the high or "upcast" side of the fault.

When dip-faults traverse anticlinal and synclinal folds, they necessarily cause similar apparent horizontal shifting of outcrops. But as the outcrops are shifted by one and the same fault in different directions, it is obvious that this effect cannot be the result of horizontal movements. This is made clear by the models in Figs. 43, 44. In Fig. 43, A represents a block of strata arranged in the form of a syncline which is eventually fractured along the line *f f*, and displaced as shown in B. When the strata on the high side of the fault have been removed by denudation, and the whole area has been reduced to the same level *s s*, the outcrops will exhibit the appearance shown in C. It is evident, therefore, that a fault traversing a syncline has the effect of causing a mutual approach of the outcrops on the high side. When a fault cuts across an anticline, on the other hand, the effect of denudation, as will be seen from Fig. 44, is to bring about an apparent recession of the opposing outcrops on the high or upcast side.

Strike-faults or, as they are often termed, *longitudinal faults*, are so called because they trend in the general direction of the strike or the axes of the folds of a district. They also affect the outcrops, but in a different way from dip-faults. They do not cause any apparent horizontal shifting, and therefore are not so easily detected, in many cases at least, as ordinary dip-faults. Sometimes their downthrow is in the same direction as the inclination of the strata; at other times it is in the opposite direction or against the dip. In Fig. 45, A represents, as before, a block of strata traversed by a strike-fault *f f*, the vertical displacement being shown in B. In this case the *downthrow of the fault is in the*

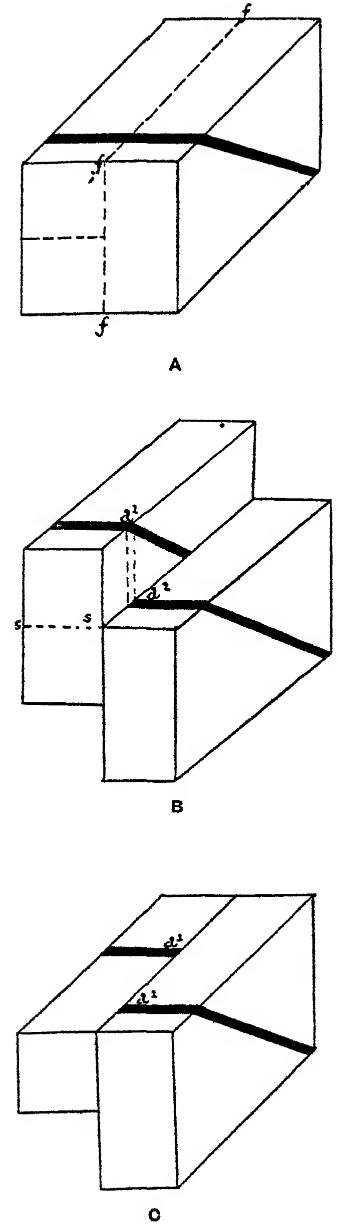

f
f
f
A
d¹
d¹
s
s
B
d¹
d¹
C

Fig. 42.—Effect produced on Outcrops by Dip-fault.

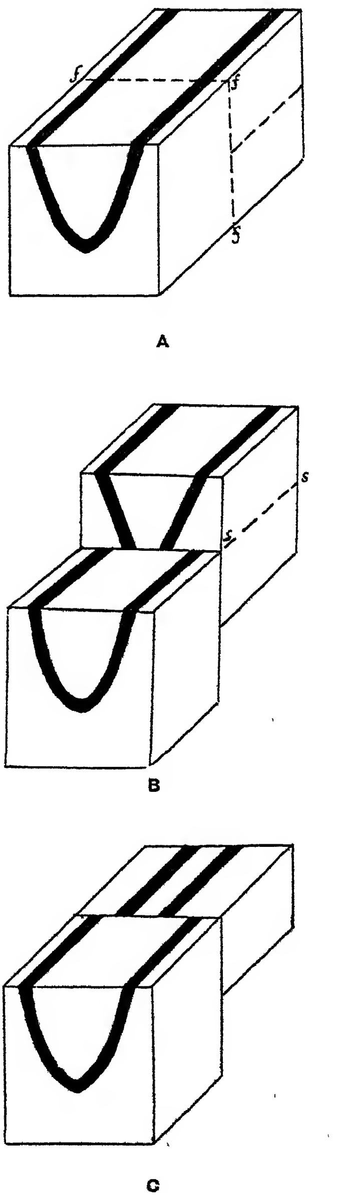


Fig. 43.—Effect produced on Outcrops by Dip-fault traversing Synclinal Strata.

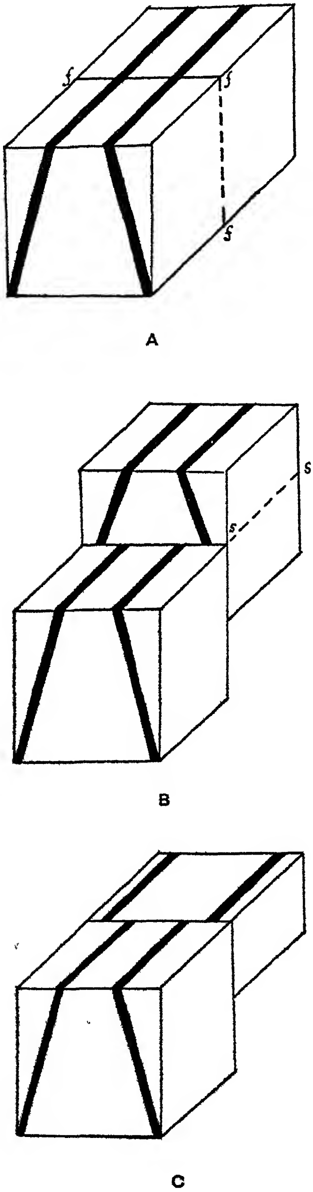


FIG. 44.—EFFECT PRODUCED ON OUTCROPS BY DIP-FAULT TRAVERSING ANTICLINAL STRATA.

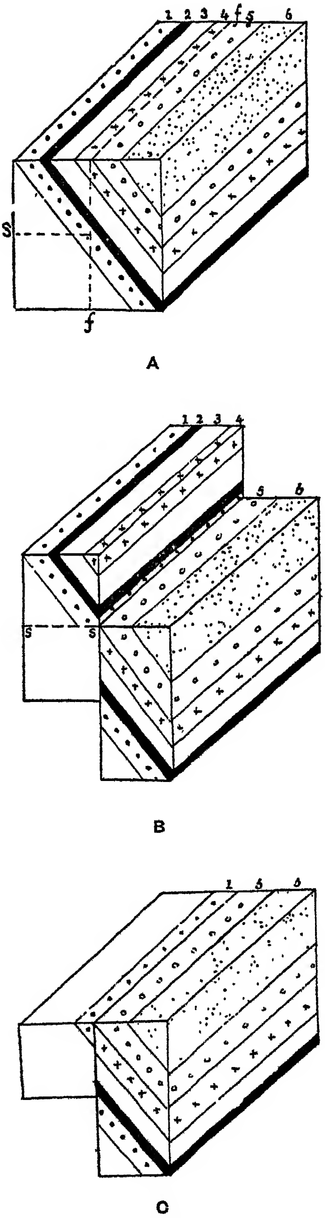

1 2 3 4 f 5 6
S
f
A
1 2 3 4
5 6
S S
B
1 5 6
C

FIG. 45.—EFFECT PRODUCED ON OUTCROPS BY STRIKE-FAULT WITH DOWNTHROW IN THE DIRECTION OF DIP.

direction of dip. Removing the higher portion of the model above the line *s s* in B, we have the ground-plan as shown in C. Obviously, the effect of a fault hading in the direction of dip is to cut out strata—to carry their outcrops below the surface. In the area represented by the model A, we have a considerable succession of strata numbered consecutively, 1, 2, 3, 4, 5, 6. The same beds are shown in C, but some no longer crop out at the surface, but under the surface and against the dislocation. The beds 2, 3, and 4 are cut out, as it were.

Let us now take the case of a strike-fault which has a *downthrow against or in the opposite direction to the dip* of the strata. The effect of such a fault is precisely the reverse of that just described. Instead of cutting out strata at the surface it causes outcrops to be repeated. A glance at the models (Fig. 46) will explain how that happens. In A we have the strata before displacement is effected along the line *f f*. B shows the dislocated strata, and in C we have the effect produced at the surface by the removal of the block projecting above the line *s*—the truncated ends of the beds 1, 2, and 3, being brought up, as it were, and caused to crop out again, so as to present the deceptive appearance of six beds all dipping in the same direction.

Strike-faults are apt to be overlooked when they coincide more or less closely with the line of bedding. An observer, for example, who should traverse either of the areas represented in the models C, C (Figs. 45, 46), might easily fail to detect any evidence of dislocation, and might be led to suppose that he had passed across continuous successions of strata; and thus, in the one case, he would assign too small, and in the other too great, a thickness to the series. It is rarely, however, that a fault follows the strike continuously; more usually it undulates from one side to another, and whenever it leaves the strike its presence is at once betrayed by the more or less abrupt truncation of the strata which it produces. But even when it keeps closely to the line of strike, variations in the amount of its downthrow will nevertheless indicate its presence. As will be shown presently, the throw of every fault necessarily varies. Each begins at zero—then gradually or more rapidly, as the line of fracture is followed, the downthrow increases until its maximum is reached, after which it diminishes until zero is again reached at its further extremity. In other words,

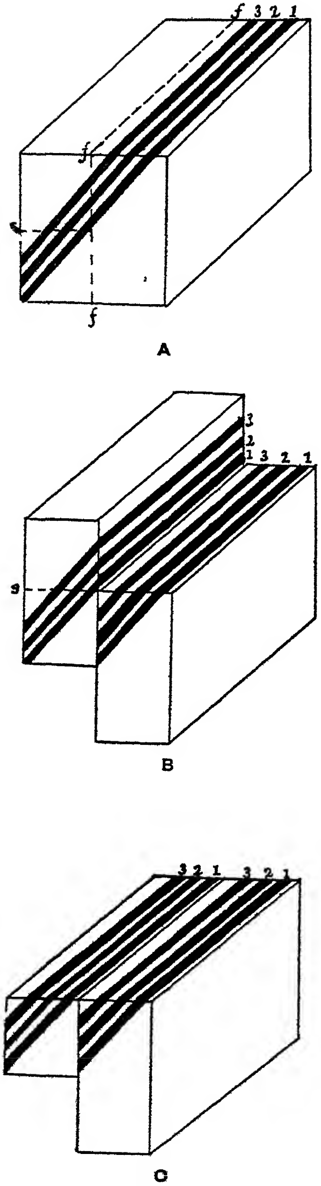

f 3 2 1
f
s
f
A
3
2
1 3 2 1
s
B
3 2 1 3 2 1
C

FIG. 46.—EFFECT PRODUCED ON OUTCROPS BY STRIKE-FAULT WITH DOWNTHROW AGAINST THE DIP.

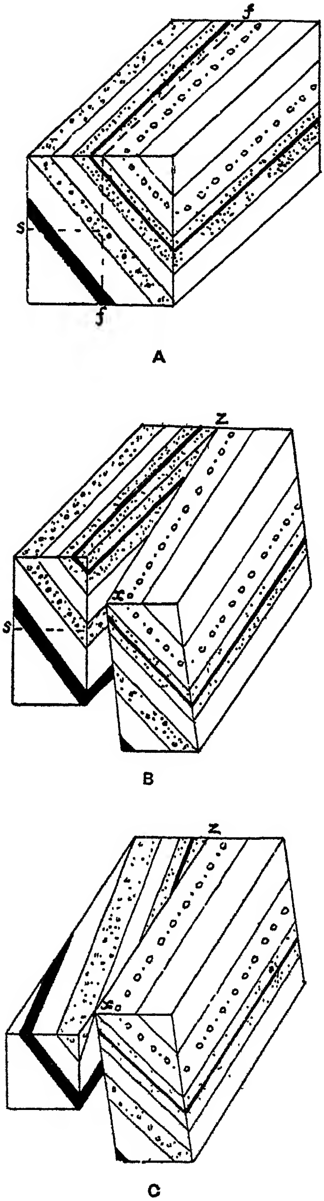

f
s
f
A
z
x
s
B
z
x
C

FIG. 47.—EFFECT PRODUCED ON OUTCROPS BY STRIKE-FAULT WITH A DIMINISHING DOWNTHROW.

the crust is cracked along a certain line and sinks or sags on one side of that line—the depression being greatest, as a rule, at a point midway between the two ends of the rent. The effect of a strike-fault with such a diminishing or increasing downthrow is illustrated by the models (Fig. 47). As in preceding illustrations, A represents the strata before displacement along the line *f f* has been effected. In B the fault has taken place, the downthrow being at a maximum at *x*, but gradually diminishing towards *z*, where it dies out. When the portion projecting above *s* is removed we have the appearance shown in C, which represents the surface produced by denudation. It will be observed that upon the upcast or high side of the fault lower beds successively appear as the fault is followed from *z* to *x*.

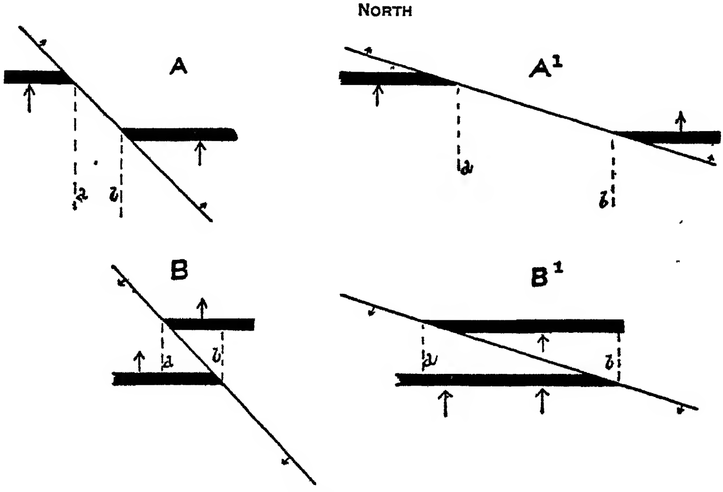
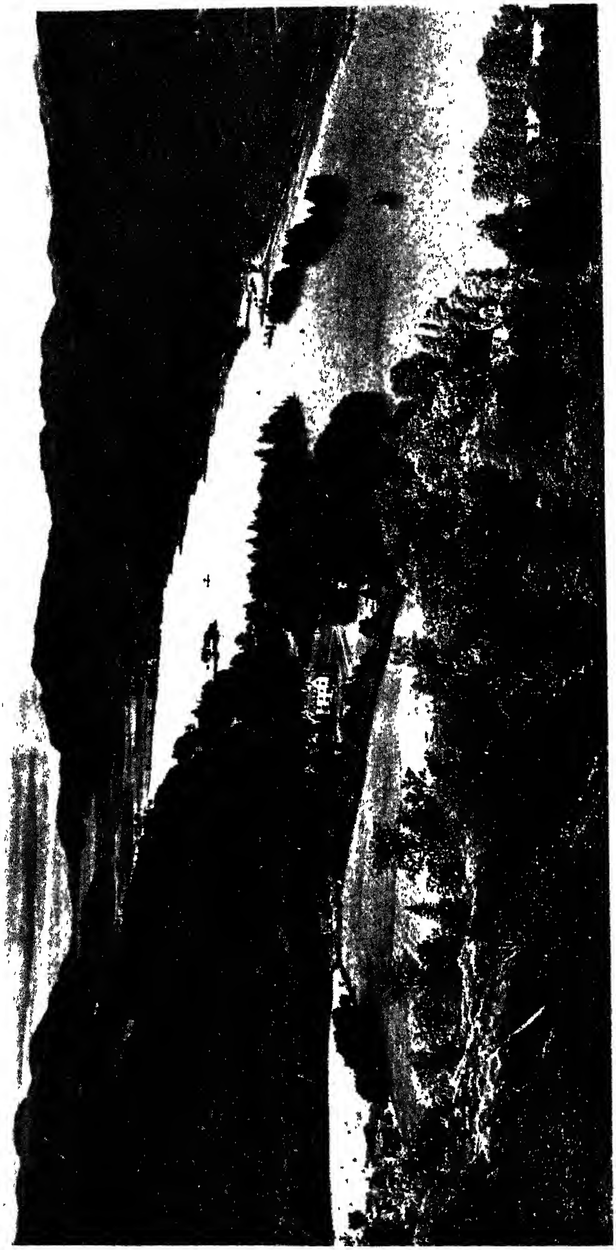


FIG. 48.—EFFECT PRODUCED ON OUTCROPS BY OBLIQUE FAULTS.

Oblique Faults.—The effects produced by normal dip-faults and longitudinal or strike-faults are so marked that the one kind of fault cannot be confounded with the other. Dip-faults, however, do not always or even often traverse the outcrops at right angles, nor do longitudinal faults invariably keep to the line of strike. Oblique dip-faults and oblique strike-faults are of common occurrence, and occasionally the obliquity of a fault becomes so great that the dislocation cannot be properly termed either a dip-fault or a strike-fault. In Fig. 48, for example, A represents a coal-seam dipping due north, cut at an angle of 45° by a fault having its downthrow towards the north-east. It is obvious that this fault behaves partly as a dip-fault, inasmuch as it produces apparent horizontal shifting of the strata, and partly as a strike-fault, for it cuts out a portion of the outcrop. The fault represented in A^1 traverses a coal-seam at a more acute angle, and thus has rather the character of a strike-fault than a dip-fault, for it cuts out a much larger part of the outcrop. The faults represented in B and B^1 have downthrows in the opposite direction to those shown in A and A^1, but otherwise they resemble the latter in behaving partly as dip-faults and partly as strike-faults. It will be observed, however, that the downthrows are in an opposite direction. In B, for example, a coal-seam is represented, as before, dipping due north, and intersected by a north-west and south-east dislocation hading towards south-west. The fault produces the effect of a dip-fault by shifting the outcrop, but since it crosses the strike obliquely it causes a duplication of the outcrop between *a* and *b*. The fault shown in B^1 approximates much more closely to the strike, with the necessary result that a longer stretch of outcrop is repeated. These diagrams should be compared with the models shown in Figs. 42, 45, and 46. From a study of the latter it becomes evident that the effects produced by the fault in A^1 more closely resemble those caused by the strike-fault C (Fig. 45), than those that result from the normal dip-fault C (Fig. 42). Again, the most notable feature in the diagram B^1 is the duplication of the outcrop—the fault having, for some considerable distance, the effect upon the outcrop of a strike-fault with downthrow against the dip (Fig. 46).

Groups of Faults.—Although faults often occur singly, more particularly when their throw is small—yet they frequently form associated groups or systems. Great dislocations, for example, which often extend for long distances, are rarely unaccompanied by parallel faults having downthrows in the same or opposite directions. Sometimes these parallel dislocations are so numerous and occur so closely together that it is often hard to say which is the main or principal fault. When the downthrow of all or most of them is in the same direction, the result is practically the same as if there had been only one dislocation with a large downthrow (see Fig. 49). Successive parallel strike-faults having their downthrows in

PLATE XLI



LINE OF GREAT GLEN FAULT, LOCH OICH TO LOCH NESS.

Photo by R. M. Adam.

[*To face page* 165

one direction, or with some in one direction and some in another, often occur in our coalfields, where they are known as **step-faults**—an appearance shown in the diagram (Fig. 50). Such faults, when their downthrow is in the same direction as the dip, have the effect, as already indicated, of preventing certain beds from cropping out at the surface. On the other hand, a succession of step-faults, each with its downthrow against the dip, may cause a coal-seam to crop out again and again. (See Fig. 51, which should be compared with the models in Fig. 46.)

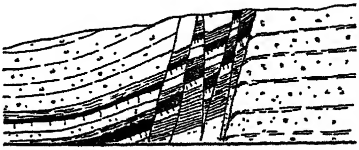


FIG. 49.—COMPLEX FAULT.

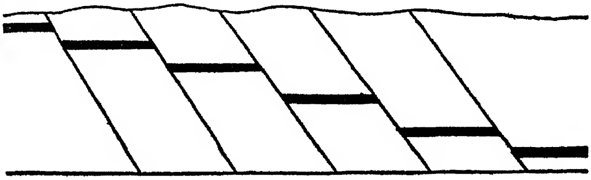


FIG. 50.—STEP-FAULTS.

When parallel or approximately parallel faults belonging to the same system hade towards each other, they produce the phenomena of **trough-faults** (Fig. 52, *t t*). When they hade away from each other we have the converse structure of **ridge-faults** (Fig. 52, *r*).

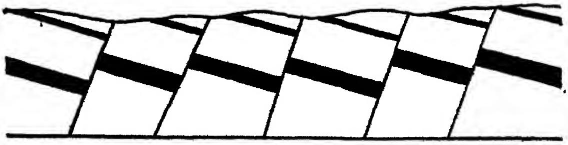


FIG. 51.—STEP-FAULTS HADING AGAINST THE DIP.

Faults having the same trend, but with their downthrows in different directions, often coalesce, and either suddenly terminate at the point of junction, or one may die out and the other continue with usually a diminished throw. But when approximately parallel faults, having their downthrows in one and the same direction come together, they almost invariably continue as a single fault, often with an increased amount of downthrow.

The amount of throw of normal faults is, as we have seen, very variable—not exceeding a few feet in some cases, while in others it may reach thousands of yards, and thus bring into juxtaposition rocks of vastly different ages. The smaller faults usually extend for very short distances, while the greater ones may continue for hundreds of miles. The course of a large fault is usually approximately straight or gently sinuous, but not infrequently it is curved. Such faults may begin as a mere crack, or as a series of two or more converging fissures, with little or no accompanying rock-displacement. But as it continues, the throw gradually augments until a maximum is reached, after which it usually decreases until finally the fault dies out as it began—in a mere crack or series of cracks. In many cases, however, the throw varies irregularly from point to point.

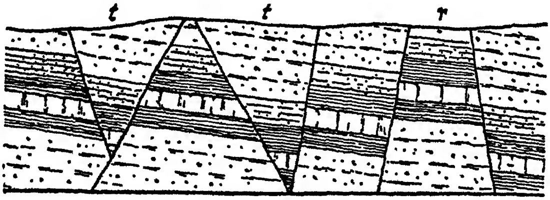
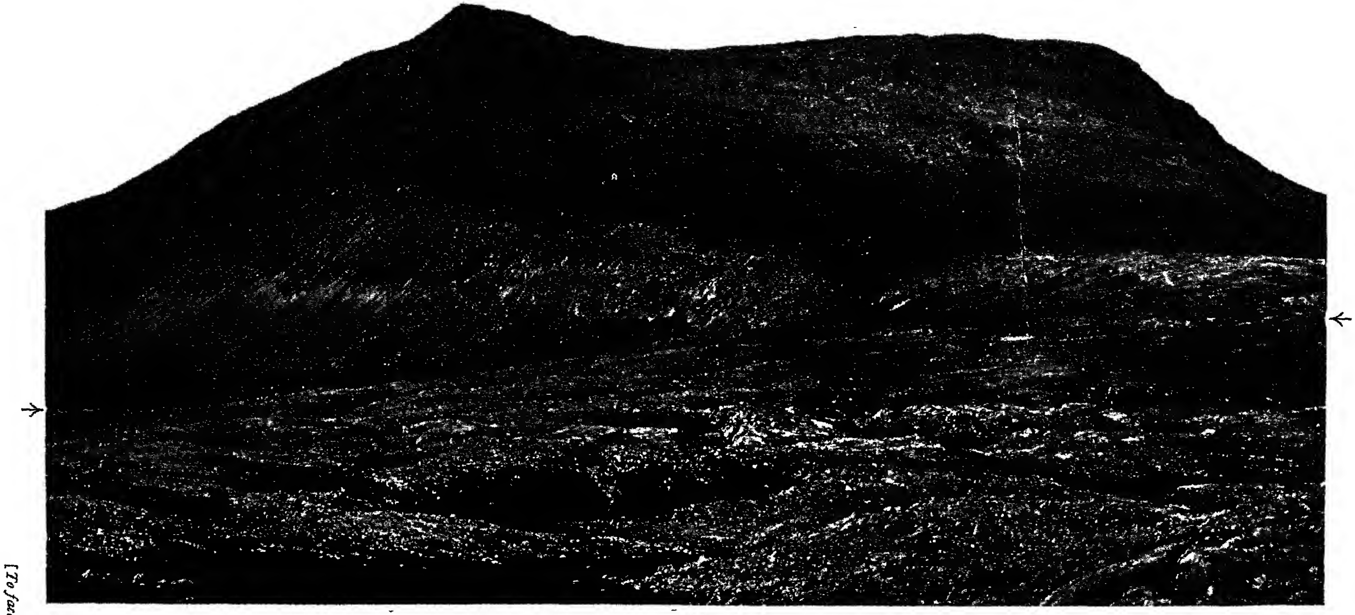


FIG. 52.—TROUGH-FAULTS AND RIDGE-FAULTS.

The phenomena presented by the two conjugate systems of **strike-faults** and **dip-faults** which are so characteristic of many regions, lead to the belief that these faults are of the same age—that they came into existence contemporaneously. This is suggested by several considerations to which reference will presently be made. But it may be pointed out here that strike-faults of contemporaneous age rarely or never cross each other; and the same is the case with dip-faults belonging to one and the same period of disturbance. One fault may, and often does, run into another, but it coalesces with it, and does not diagonally intersect it. When strike-faults are more powerful than the dip-faults of the same district, which is usually the case, the latter are intercepted by and do not cross the former. And similarly, when the dip-faults are stronger than the strike-faults, they cut these off.

Shifting of Faults.—This latter rule is so general, that when we find one fault crossing and shifting another, we may

PLATE XLII



MEALL A GHIUBHAIS, BEN EAY, ROSS-SHIRE. A mountain consisting mainly of more ancient rocks which have been pushed from left to right over the Cambrian formations along the Reversed Fault, indicated by the feature between the two arrows.

Photo by H.M. Geological Survey.

[*To face page* 166

reasonably suspect that the two faults belong to different periods of disturbance. The relative age of intersecting faults is at once revealed by the fact that the younger dislocation shifts the older, just in the same way as any fault displaces strata. The phenomena are illustrated by the diagram (Fig. 53), where *a a* is obviously the older fault, since it is displaced by the other (*b b*).

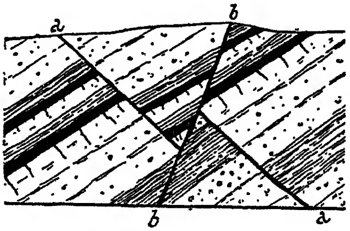


FIG. 53.—SHIFTING OF ONE FAULT BY ANOTHER.

Displacements of this kind are of common occurrence in much-disturbed regions, and prove that such areas have been rent and dislocated at separate—often widely separate—periods. In countries where ore-bearing veins are well developed, these frequently occupy lines of dislocation, which intersect at various angles. In such regions, therefore, the direction or trend of conjugate systems of faults and their relation to other similar systems have been very carefully studied, and we now know that the dislocations of a region may belong to two, three, or more periods of crustal disturbance. In Fig. 54 we have a model showing three lines of faulting, of which it is obvious that the dislocation *a a* must be the

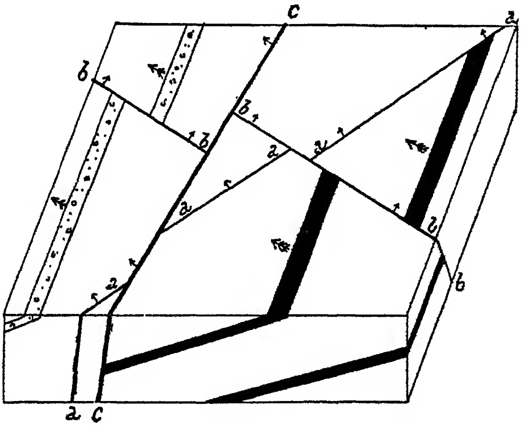


FIG. 54.—INTERSECTING FAULTS.

The feathered arrows indicate dip of strata; the small arrows show downthrow side of faults.

oldest, since it is shifted by the fault *b b*; while the latter in its turn is shifted by the fault *c c*, which, therefore, must be the latest of the series.

REVERSED FAULTS. These faults are so termed because the hade is not in the direction of downthrow, as is the case with normal faults, but in the direction of upthrow (Fig. 55). Lower or older rocks on one side of the dislocation have been thrust up over higher or younger rocks on the other side. The hade of a reversed fault, especially if it be a great displacement, is usually further inclined from the vertical than the hade of a correspondingly large normal fault. In some cases, indeed, an extensive reversed fault approaches horizontality (Figs. 61, 63) and then it is termed a *thrust-plane*. The rocks along the line of a reversed fault are often much compressed, crushed, and broken. Not infrequently, indeed, such a fault is marked throughout its whole extent by a belt of shattered and crushed rock, in which friction-breccias, friction-conglomerates, mylonites, and flinty-crush rocks may all be met with. The rocks in the immediate proximity are also often more or less metamorphosed.

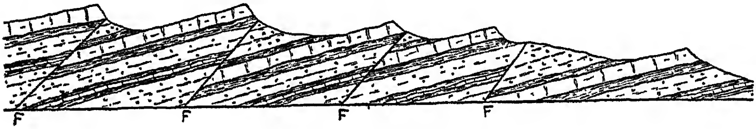


FIG. 55.—REVERSED FAULTS.

Reversed faults are of comparatively rare occurrence among horizontal and gently inclined strata. They are encountered, however, in large numbers in regions of highly folded and compressed rocks. Like normal faults, they frequently bear an obvious relation to rock-folds, and their phenomena will be better understood if considered in connection with the general question of the origin of faults.

TRANSCURRENT FAULTS.—It has been explained that the apparent horizontal shifting produced by normal faulting is really the effect of denudation. Other faults are known, however, where actual horizontal shifting on a large scale can be readily demonstrated. Such transcurrent faults are vertical or highly inclined and often extend for long distances. They are neither downthrows nor upthrows, movement having taken place in a lateral direction, so that the walls of the faults are slickensided horizontally. Not infrequently the rocks along the lines of these faults are much crushed and shattered ; sometimes, indeed, they form broad " shatter-belts."

There can be little doubt that transcurrent faults are due to tangential pressure, and in many cases they are associated with highly folded and overthrust strata. For Alpine dislocations of this type Suess used the term *blatt*, and in the English version of his *Face of the Earth* Miss Sollas translated this word as *flaw*. According to Suess flaws are more or less, but not always precisely, at right angles to the strike of the folds. In the first edition of this book James Geikie termed such faults *transcurrent faults* or *transverse-thrusts*. In later editions he emphasised their genetic relations to overthrusts and stated that they are confined to translated rock-sheets. For similar transcurrent faults in the Folded Jura, Collet has used the term *tear fault*, which was first used by Marr for certain faults in the Lake District of England, which show actual lateral shifting of outcrops. Dislocations of this type, however, are not necessarily confined to translated rock-sheets—they may affect also deeper rocks in the earth's crust. For such faults generally the terms transcurrent fault and *wrench fault* are both commonly used in this country. The expression *strike-slip fault* is widely used by American geologists as a general term for faults with dominant horizontal movement along a vertical fault plane. It does not necessarily imply relation to overthrusting.

Among the best-known examples of transcurrent faults are those met with in the Alps and the Jura and in the Scottish Highlands. In the western part of the Folded Jura, for example between Salève and Neuchâtel, no fewer than eight important tear faults occur, with lateral displacements ranging from 300 metres to 10 kilometres. The greatest of these faults, that between Vallorbe and Pontarlier, cuts the associated folds at an angle of 55°. A remarkable strike-slip fault in East Fife, the Ardross fault, described by Dr G. A. Cumming, has dislocated and displaced for a distance of 4000 feet two of the well-known volcanic necks of the Elie district. Among the more striking wrench faults of the Scottish Highlands may be mentioned the Strathconon fault and the Loch Tay fault, each with a lateral displacement of at least five miles. Recently Dr W. Q. Kennedy has adduced evidence which leads him to conclude that the Great Glen fault is also a transcurrent or wrench fault with the extraordinary lateral displacement of approximately sixty-five miles. This fault has

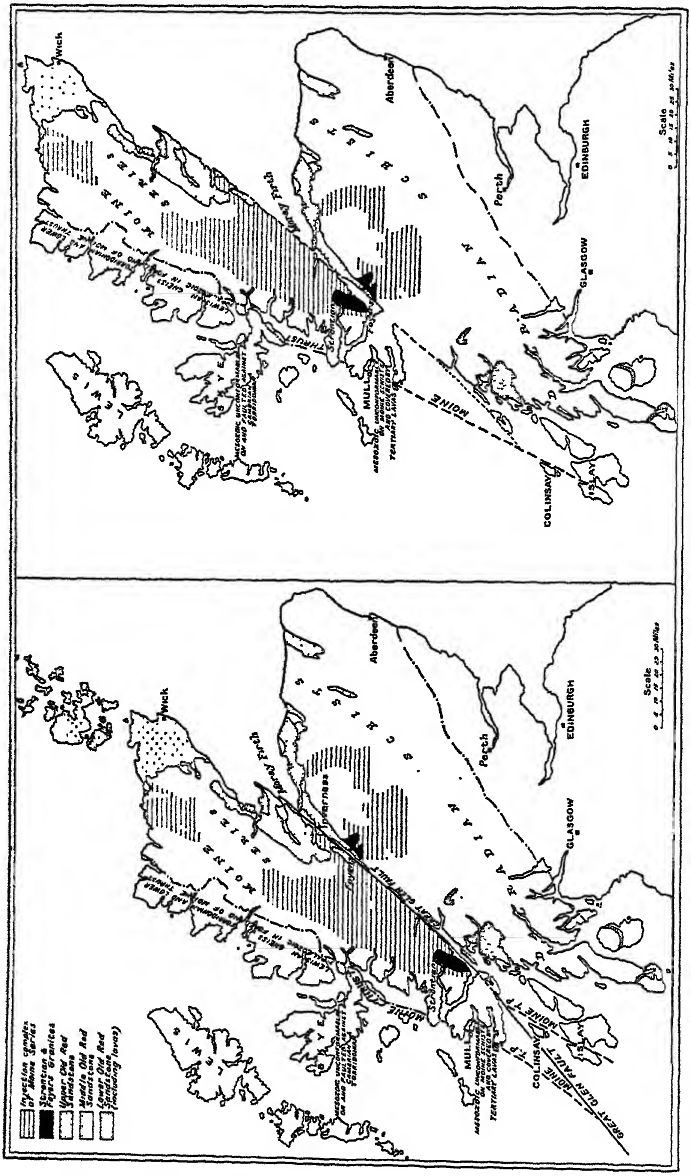
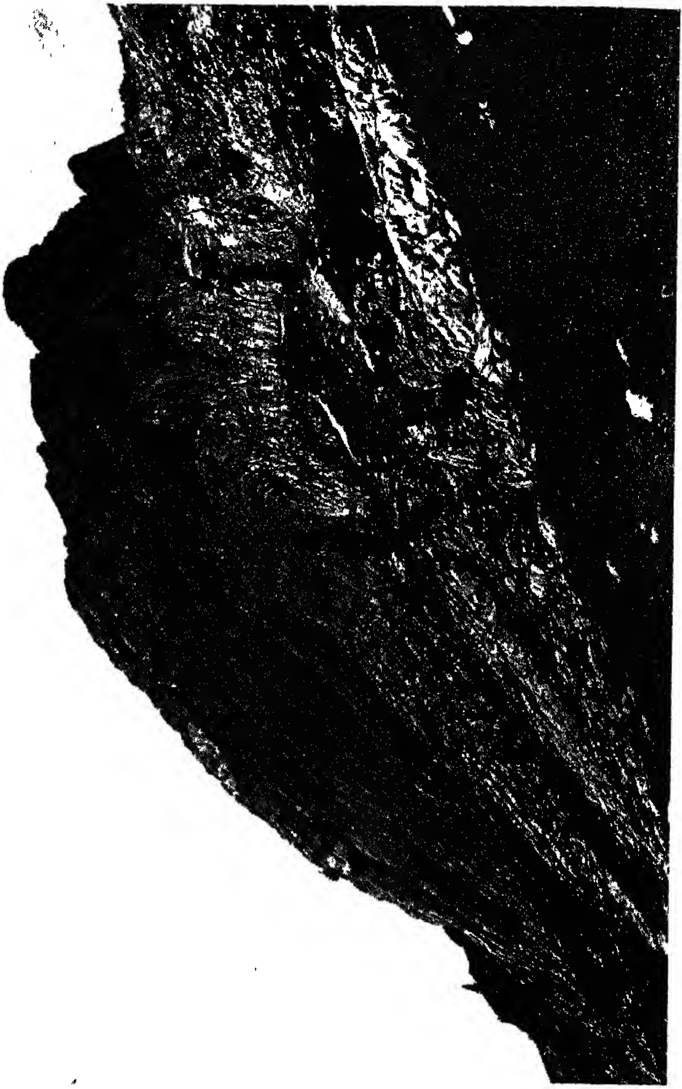

Wick
Aberdeen
Edinburgh
Perth
Glasgow
Scale
Moray Firth
Inverness
Strontian
Foyers
Moine Series
Schists
Skye
Lewis
Mull
Colinsay
Islay
Moine Thrust
Great Glen Fault
Injection complex of Moine Series
Strontian & Foyers Granites
Upper Old Red Sandstone
Middle Old Red Sandstone
Lower Old Red Sandstone (including lavas)

Fig. 56.—The Maps show respectively (*a*) on the left, the Present Positions of the Injection Complex of the Moine Schist Series, the Strontian and Foyers Granites, and the Moine Thrust-plane, (*b*) on the right, their Supposed Positions prior to the Wrench-faulting along the Line of the Great Glen. (After W. Q. Kennedy.)

displaced the great belt of regional injection which affects the Moine Schists. It has also truncated the Strontian Granite

PLATE XLIII



ASYMMETRICAL FOLD OF THE "SCHRATTENKALK," LEANING OVER TOWARDS NORTH: SÄNTIS MOUNTAINS.

Photo, Wehrli, Zurich.

[*To face page* 171

Complex, the southern portion of which is represented by the Foyers Granite which outcrops on the south side of the fault some sixty-five miles to the north-east. Dr Kennedy's interpretation of the Great Glen fault confirms the supposed presence of the Moine Thrust-plane in the island of Islay. (See Fig. 56 and Plate XLI.).

Origin of Faults.—Although we have yet much to learn as to the origin of faults, there are certain conclusions which seem fairly well established. From our descriptions of the phenomena of **normal faults,** the student has doubtless gathered that these displacements are most satisfactorily explained by the view that they are true downthrows and not upthrows. Their somewhat constant relation to the dominant folds of a region seems to suggest that they are, like many joints, the result of torsional strain. We may suppose that the rents were produced or commenced at the time the strata were being folded. But folding implies, of course, lateral compression, and it does not seem likely, therefore, that the fractured rocks could subside so long as compression continued. When this movement had ceased, however, the bulged-up crust, relieved from lateral pressure, would tend to sink again, and subsidence would naturally take place along the cracks and fissures which had already come into existence. The whole area we may think of as being split up into a series of rectangular blocks of varying size, each block defined by fissures, some of which would be inclined in one direction and some in another. In this way a long rectangular block, defined by two parallel strike-faults inclined towards each other, would have a relatively narrow base; while the adjoining block, defined by two parallel strike-faults inclined away from each other, would have a relatively broader base. Thus, when gravitation came into play and the fractured rock-masses commenced to sink, those with a relatively narrow base (presenting as they would a smaller area to pressure) would tend to sink more readily than the broader based segments that adjoined them. In short, downthrow would take place in the direction of the hade. It must be noted, however, that some amount of lateral pressure would be exerted by the several subsiding masses, which might now and again result in local distortion, crushing, and fracturing, such as so frequently accompany normal faults. This lateral pressure would also account for the fact that now and again the rocks on both sides of these faults are turned or bent upwards or downwards (see Fig. 57).

Apart, however, from any theoretical explanation of **normal faults,** we have direct evidence to show that such faults are occasionally so intimately connected with folds and flexures that we can have no doubt that they are contemporaneous and due to one and the same crustal movement. Again and again, for example, large strike-faults, when traced continuously, have been found to die out in a flexure. In the case of monoclinal flexures it is not hard to see how that should be. Strain or tension must be set up along the margin of a sinking area. If subsidence should take place within a region built up of horizontal strata, the horizontal position of the rocks along the boundary or margin of the sinking area will be interfered with. The pull or drag of the descending mass will cause the strata of the adjacent stable area either to bend over or to snap across. Should the movement be slow and protracted, the rocks will probably at first yield by bending. They will be turned downwards and compressed, it may be, by stretching. But should the movement continue, they must eventually give way, and a fold will thus be replaced by a fracture. Towards one or both ends, therefore, we should expect such a fault to die out into a simple flexure or monocline (see Fig. 58).

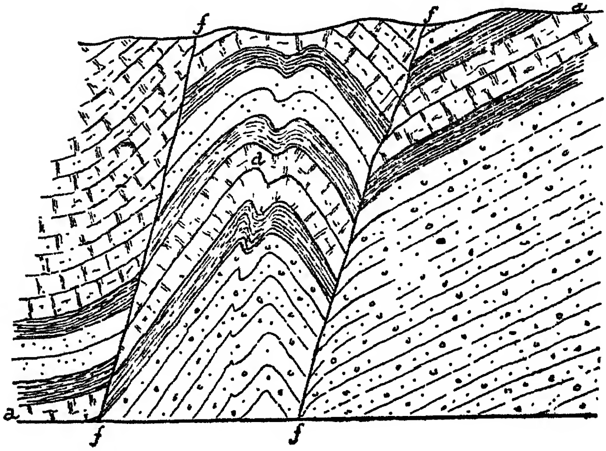


FIG. 57.—PARALLEL FAULTS WITH DISTORTED STRATA BETWEEN.

Although faults of the kind described may be considered the result of direct subsidence, it is obvious that they might equally well have resulted from movements of elevation. During the slow uplifting of a broad plateau, tension will come into play along the margin of the rising area. Flexures will then be formed, and these will eventually be replaced by

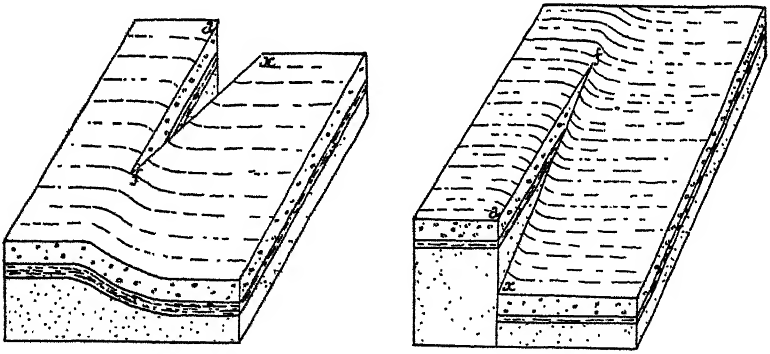
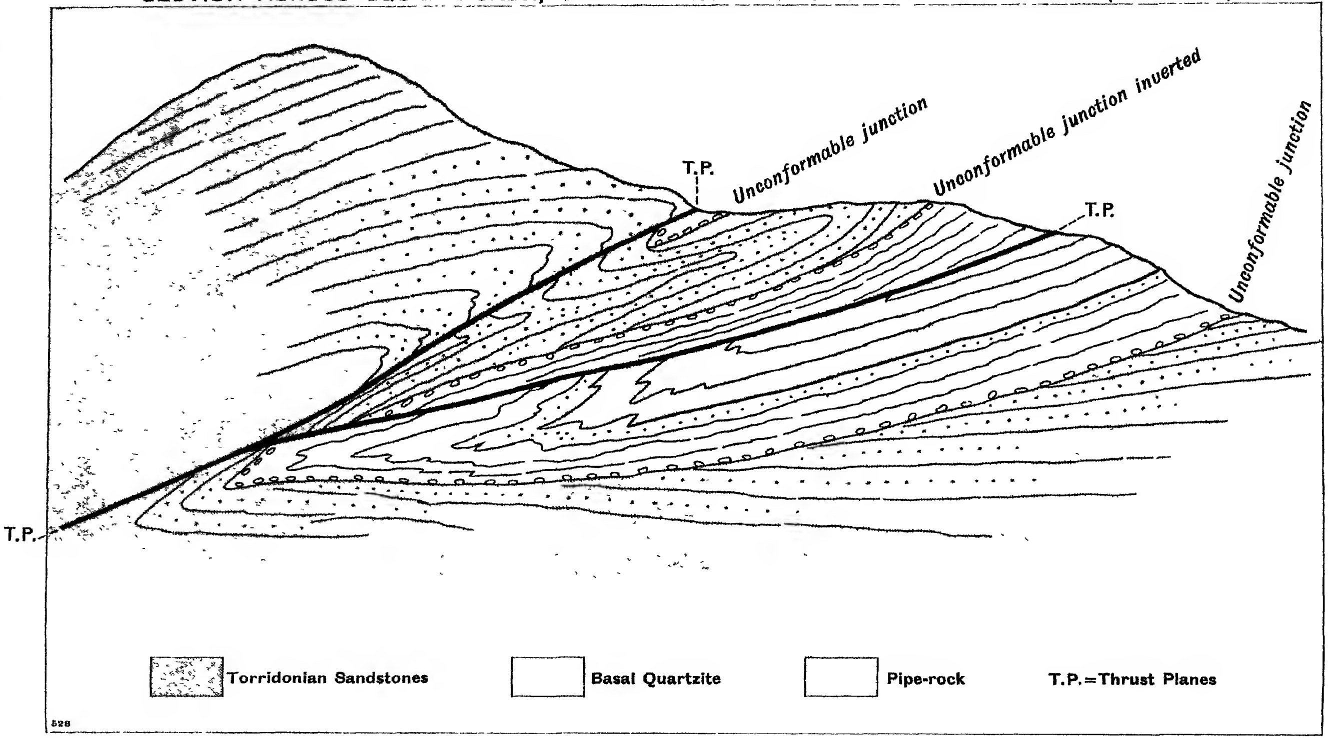


FIG. 58.—MONOCLINAL FLEXURE PASSING INTO A NORMAL STRIKE-FAULT, VIEWED IN OPPOSITE DIRECTIONS.
(After Chamberlin and Salisbury.)

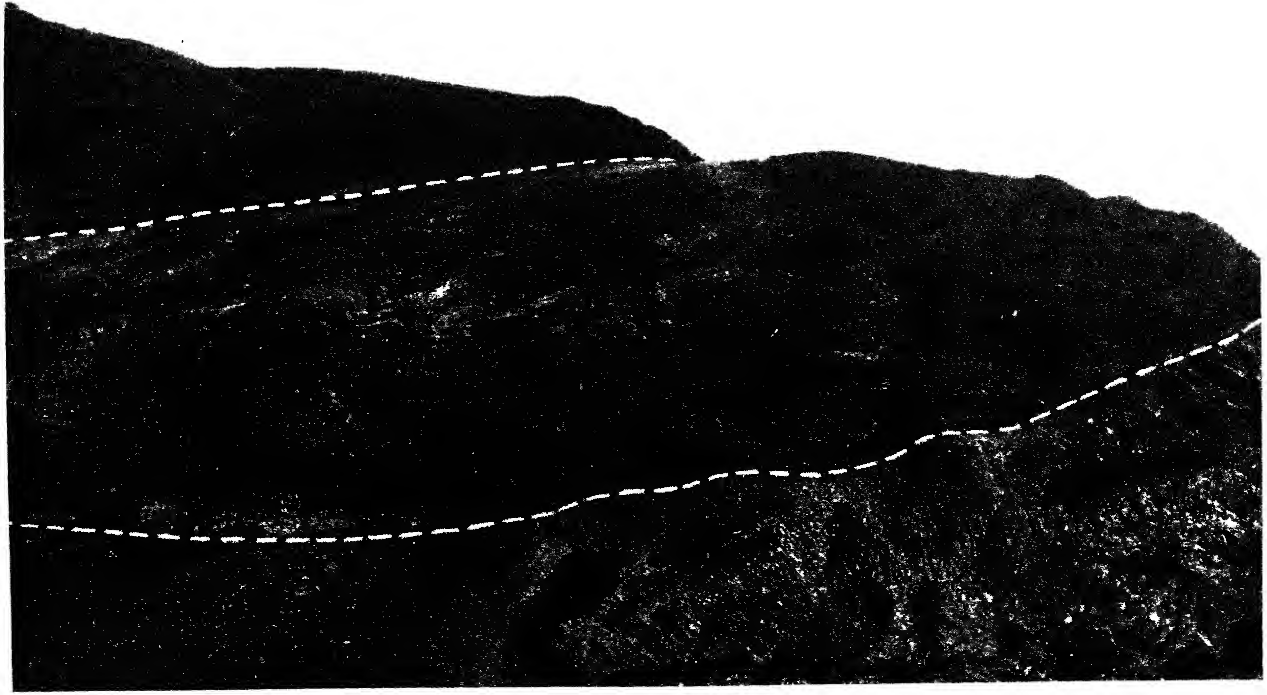
PLATE XLIV

SECTION ACROSS SGURR RUADH, SHOWING INVERSIONS AND THRUST-PLANES (*B. N. Peach*)


T.P.
Unconformable junction
Unconformable junction inverted
T.P.
Unconformable junction
T.P.
Torridonian Sandstones
Basal Quartzite
Pipe-rock
T.P.=Thrust Planes
528

[To face Plate XLV
Between pages 172-173

PLATE XLV



North Face of Sgurr Ruadh, Achnashellach Forest, Ross-shire. White lines show edges of Thrust-planes.

Photo by H.M. Geological Survey.

[*To face* Plate XLIV

[*Between pages* 172 *and* 173

rents and dislocations. The resulting structure would thus be the same as if folding and faulting had been caused by a movement of subsidence. Thus, in Fig. 58, the fault *f* might have been caused either by the subsidence of the strata at *x*, or by the upheaval of the strata at *a*. But as the dominant movement of the earth's crust must be one of subsidence, it is preferable to consider all normal faults as downthrows rather than upthrows. Nevertheless, our knowledge of the nature of crustal movements is not so complete that we can deny the possibility, or even the probability, that normal faults may now and again have come into existence during movements of upheaval.

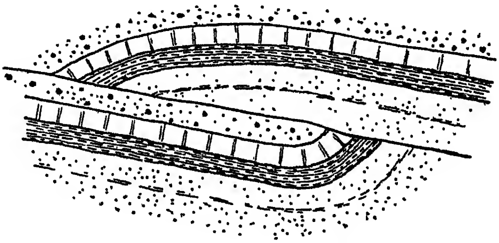


FIG. 59.—REVERSED FAULT REPLACING MONOCLINAL FLEXURE.

Reversed faults do not often occur in regions where the rocks show little trace of disturbance. This seems to be due to the simple fact that they are the result of lateral pressure or compression, so that they are best developed and of most common occurrence amongst highly folded and distorted rocks. Now and again, however, where monoclinal flexures have obviously resulted from horizontal movements, the flexures have yielded and given place to reversed faults (see Fig. 59). In other cases gently inclined strata, when subjected to lateral pressure, have, instead of first folding, at once yielded to the strain by snapping obliquely—and one portion of the severed mass has been pushed bodily over the other. But faults of this kind, occurring in gently inclined strata, are usually on a small scale and merely of local importance.

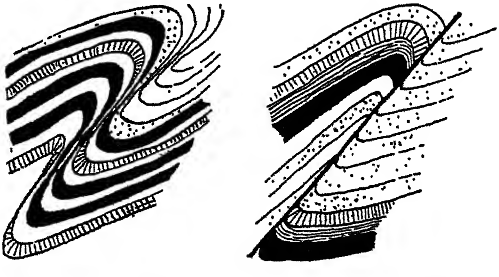


FIG. 60.—ORIGIN OF STEEPLY-INCLINED REVERSED FAULTS IN HIGHLY FOLDED ROCKS.

One of the commonest kinds of reversed fault is that known as an **overthrust** (Fig. 60). Folds, as we have seen, are the result of horizontal movement or tangential pressure. When this is excessive they are rendered more and more asymmetrical, the middle limb of each fold becoming thinner and thinner as the rock is drawn out in the direction of movement. With continued pressure the limb at length yields and the highly inclined or recumbent anticline is pushed forward—in short, the fold is dislocated and a reversed fault comes into existence. All gradations of such overthrusts may be studied in most regions of highly folded and contorted strata.

Reversed faults of the steeply-inclined character shown in Fig. 60 are of common occurrence in all mountains of uplift, but the amount of displacement is seldom considerable. In short, they are usually only of local and subordinate importance. It is frequently otherwise, however, with the displacements of recumbent folds (Fig. 61). In great mountain uplifts folds of this type often occur on a colossal scale and bear evidence of intense tangential pressure. It is therefore not surprising that in their case excessive rock-displacement should frequently have taken place—sheets of rock, thousands of feet in thickness and of vast extent, having been forced to move along approximately horizontal planes or up gentle inclines, for distances of many miles.

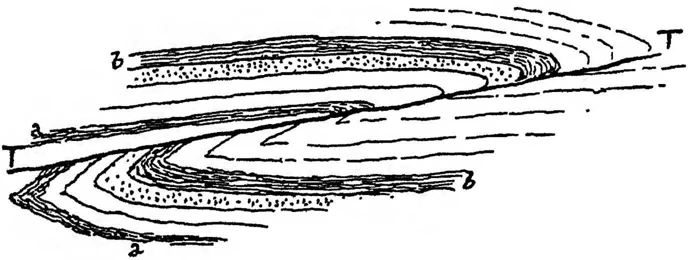


FIG. 61.—FAULTED RECUMBENT FOLD.
T T thrust-plane.

It is only within recent years that the true character of these structures has been ascertained. Formerly they were supposed to be the result of a peculiar kind of folding. In Fig. 62, A represents what used to be termed a "double-fold," caused by two overturned and flattened anticlines approaching each other from opposite directions (as shown by the arrows), and enclosing between them a great synclinal trough of much disturbed and convoluted strata. But a glance at the section shows that the opposing anticlines are quite hypothetical, for they are represented by dotted lines. According to this interpretation of the geological structure of the Glarner region it would seem as if crustal movement had taken place in diametrically opposite directions. The correct interpretation, however (see B, Fig. 62), shows that movement has been in one direction only—one extensive rock-sheet has been thrust forward from south to north over the whole region. Transported rock-sheets, whether brought forward by recumbent folding or by thrusting, are termed *nappes*. *Klippes* or *nappe-outliers* are detached parts of nappes which have escaped erosion.

Fold-faults of Alpine type, as the researches of Dr E. B. Bailey and others have shown, play an important part in the architecture of the central and southern highlands of Scotland. The immense extent of many of the folds in these regions is due largely to the fact that the rocks undergoing folding have been broken and displaced along fold-faults or *slides*, which generally lie nearly parallel to the folds themselves. Bailey, to whom we owe the term, recognises two categories of slides—*overthrusts* and *lags*. When continued movement has resulted in the elongation of the middle or reversed limb of the fold the slide has the character of an overthrust; when, on the other hand, it has led to elongation of the flanking unreversed limbs the slide is known as a lag.

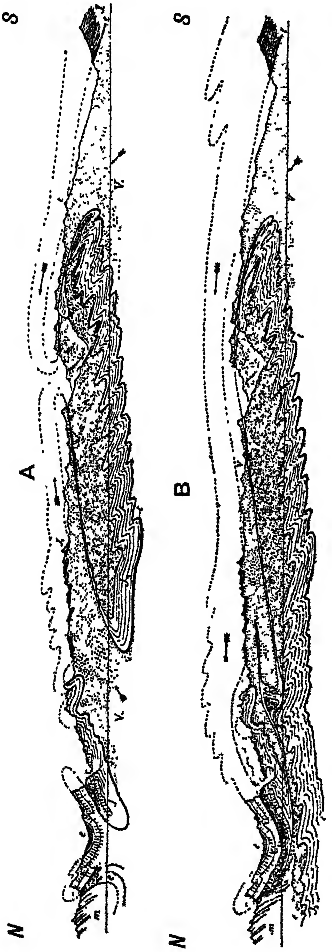


FIG. 62.—SCHEMATIC SECTIONS OF THE FOLDED STRATA OF THE GLARNER REGION, SWITZERLAND.

A. The Glarner "Double-fold" according to Escher and Heim (1870-1902).

B. The Glarner "Rock-sheet" according to Bertrand (1883), Suess (1892), Heim (1903). *m*. Molasse (Nagelfluh); *e*. Flysch; *c*. Cretaceous strata; *J*. Jurassic strata; *t*. Helvetian Trias; *V*. Verrucano (Permian conglomerates). (From Heim's *Der Bau der Schweizeralpen*.)

Although translated rock-sheets would seem frequently to have originated as much flattened or recumbent folds, the middle limb in each case having been drawn out until it thinned away and was replaced by a fault or horizontal displacement, yet it is certain that the translation of great rock-sheets has not always been preceded by folding. Very often the rocks subjected to excessive tangential pressure have yielded without any preliminary folding, the strata being broken and repeated by a series of minor thrusts or reversed faults, which lie at an oblique angle to the overlying major thrust-planes. This heaping-up of strata below the latter is known as *imbricate* or *schuppen structure* (see Fig. 63). Along the major thrust-planes enormous slices or sheets have been driven successively often for miles one over another. In the north-west of Scotland many remarkable examples of the kind occur (see Plates XLII., XLV.), some of the translated rock-sheets having travelled ten miles or more—a distance very greatly exceeded by the similar rock-sheets of Scandinavia.

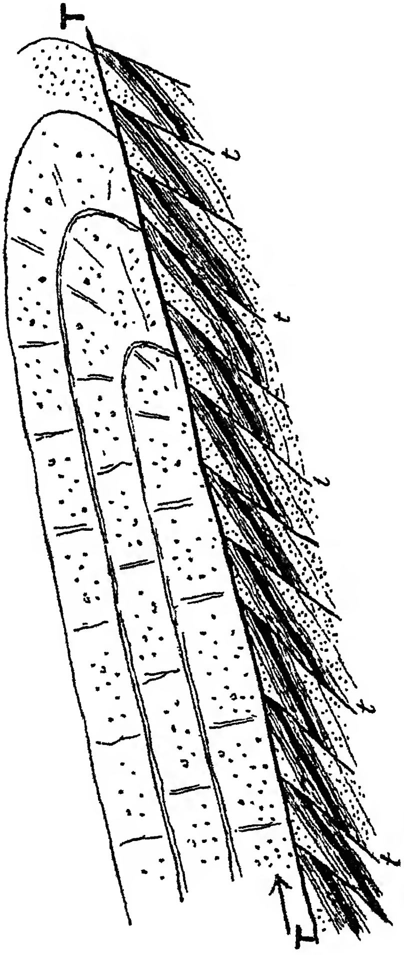


FIG. 63.—TRANSLATED ROCK-SHEETS.

t t Minor thrust-planes or reversed faults due to tangential pressure, causing frequent repetition of strata = *imbricate* or *schuppen structure*. T T Major thrust-plane along which the higher-lying rock-sheet has been driven in the direction indicated by the arrow. The appearance of folding is probably the result of friction along the thrust-plane, causing the brow of the rock-sheet to curve over and become inverted.

Plate XLV. is a view of Sgurr Ruadh, a mountain in Ross-shire. It shows the north face of the mountain along which the following series of bedded rocks crop out:—*a*, Torridon Sandstones; *b*, Basal Quartzite; *c*, Pipe-rock. The white lines are thrust-planes which traverse the hill-face in the same direction as the outcrops. Plate XLIV., for which Professor Geikie was indebted to his old colleague and friend Dr Peach, is a section taken obliquely across the mountain, and shows the general structure of the ground. From the base of the mountain up to the first thrust-plane the strata occur in their true order; thereafter, it will be seen they are inverted and have been driven forward. The two thrust-planes which appear in section on the hill-face are branches of one and the same over-thrust, as is shown in the section. The thrust-planes of the north-west Highlands are inclined at various angles, but the larger ones usually deviate most from the vertical. Not infrequently, indeed, they are almost horizontal. In the general denudation of the country these thrust-planes have now and again given rise to marked surface-features.

Travelled rock-sheets seem to characterise all "mountains of elevation." They are particularly notable in the Alps, some in that region having been driven from south to north for forty miles and more. For example, the Prealps of Chablais and the Romande Prealps, in the neighbourhood of the Lake of Geneva, are composed chiefly of Mesozoic rocks and have travelled north from the central Alpine area. They rest upon rocks (Cainozoic) much younger than themselves, and are thus mountains "without roots"—the roots occurring far to the south. The Mythen and the Rote Fluh (Plate XLVI.), overlooking Schwyz, are klippes of the Prealps. So again the well-known Matterhorn and the Dent Blanche are similarly "without roots"—the rock-sheet of which they form a part having travelled some thirty miles or more from its place of origin in Piedmont.

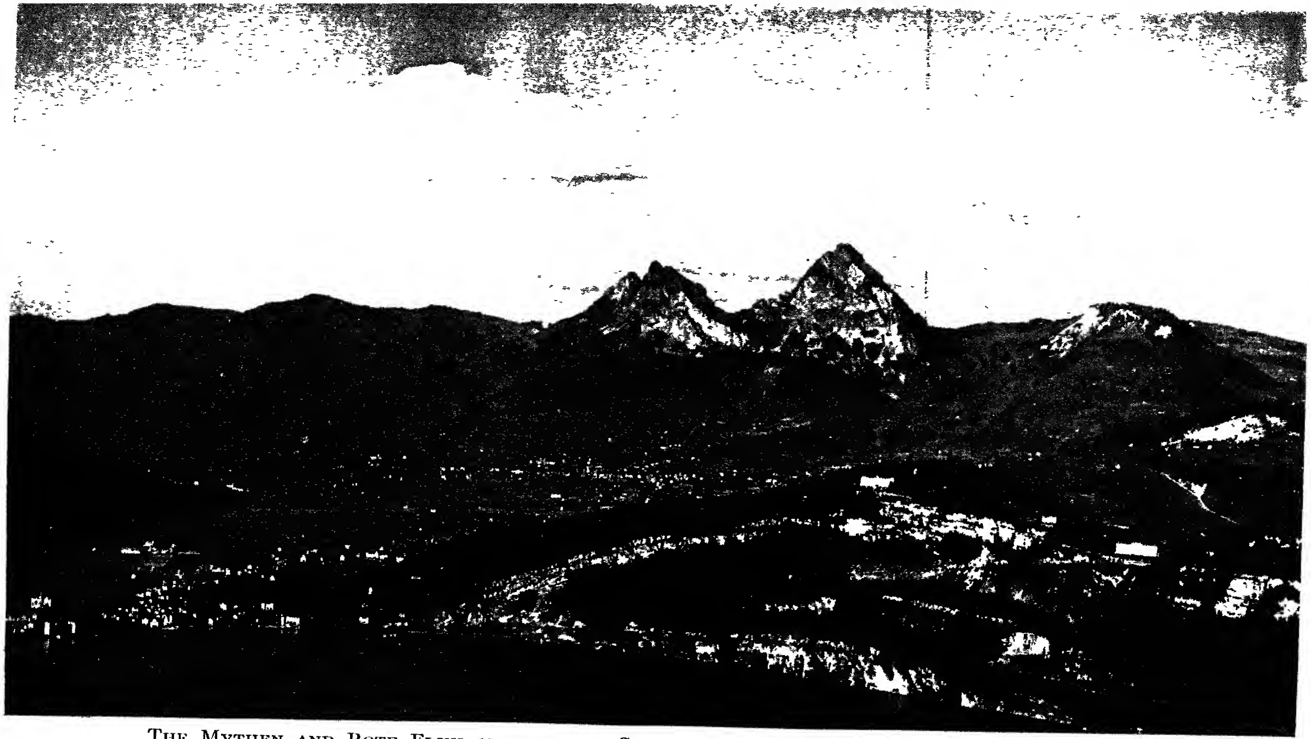
Many **Transverse thrusts** are obviously due to the same cause as overthrusts—tangential pressure—and may be looked upon as contemporaneous with the folds and overthrusts of the region in which they occur. When the strata of a growing mountain chain were being compressed and pushed forward in some particular direction, there might well be inequalities in the crustal creep. Some portions of the moving mass would advance more rapidly than others, and thus cause strain and tension, to which the crust would necessarily yield in the direction of the horizontal movement. The vertical fissures and fractures or glide-planes thus formed would, therefore, traverse the dominant folds and overthrusts of the chain more or less at right angles. Transverse thrusts of this type are confined to the translated rock-sheets, and do not affect the rock-masses over which the latter have been driven.

The general conclusion, then, to which the evidence leads is simply this, that faults are usually connected with folds, or, at all events, with horizontal movements of the crust. When strata are sufficiently compressed they usually double up, and with continued pressure eventually yield, and overthrusts take place. In some cases, however, in place of becoming folded, they at once shear, and approximately horizontal or steeper overthrusts come into existence. Again, yielding takes place, and transverse thrusts make their appearance between contiguous masses which are moving horizontally at different rates in the same direction.

The overthrusts of a highly disturbed region are often cut across by a series of normal faults, and such phenomena seem to suggest that, while overthrusts and transverse thrusts are the result of horizontal movements, the normal faults in question may have come into existence when the tangential pressure was relieved. During a great horizontal movement, the rocks are not only subjected to enormous compression, but the crust is bulged up—in other words, mountains of elevation are formed. When the forward movement ceases and pressure is relieved, the protuberant rock-masses will tend to settle down to some extent along the rents and fissures opened during the elevatory process, and normal faults will thus be produced. In the case of normal faults traversing horizontal and gently inclined strata, all we can say is that, like joints, they probably owe their origin to torsion, and since they are so commonly related to strike and dip, it seems highly probable that they also are the direct result of crustal folding. But we must not forget that many normal faults have been formed during movements of direct subsidence—which may not necessarily have been connected with any horizontal movements of the crust. Not a few extensive basin- or trough-shaped depressions are bounded by normal faults, and are obviously the result of direct subsidence or collapse of the crust.

Crustal deformation would appear usually to have been slowly effected. Under sufficient pressure solids can be compelled to flow, and hard rocks may be bent without fracturing, provided the pressure be applied gradually. It is impossible to believe that the folded strata seen in a mountain-range could have been so sharply curved and plicated without fracture, unless as the result of powerful pressure slowly applied. As regards dislocations, there is no evidence to show that great rock-displacements have been more rapidly effected than conspicuous rock-folds. We need not go so far, however, as to infer that all faults have been slow creeps. Some dislocations, may have been more or less rapidly effected. That crustal deformation, as a rule, is really a protracted process, is strongly suggested by the fact that folds and faults have come into existence in certain regions without disturbing their drainage systems. The Colorado Plateau, for example, has been split across by well-marked normal faults, some of which have a downthrow of several thousand feet, and can be followed for hundreds of miles. The same region also shows some notable folds and flexures, both faults and flexures being of relatively recent geological age. Yet none of these crustal deformations has disturbed the course of the River Colorado, which was certainly in existence long before they had been effected. It is obvious, therefore, that flexuring and faulting must have taken place so gradually, that the river was able to saw its way across the inequalities as fast as these appeared. Similar evidence to the same effect is supplied by the river-valleys of the Himalayas. It is well known that the sub-Himalayan ranges are composed of materials derived by existing rivers from the central ranges of the great chain. The materials referred to form massive accumulations which have been disturbed and upheaved, the axes of the flexures crossing the river-valleys more or less directly. Here, then, it is evident that "the rivers are older than the hills they traverse, and that the gorges have been gradually cut through the hills as they were slowly upheaved." Yet another example may be

PLATE XLVI



THE MYTHEN AND ROTE FLUH OVERLOOKING SCHWYZ, SWITZERLAND. [Mountains without "roots"; composed of Mesozoic strata resting upon the Eocene Flysch.]

Photo by Wehrli, Zurich.

[*To face page* 178

cited from our own Continent. Deep borings have shown that the Pleistocene deposits in the valley of the Rhine in Hesse occupy a profound hollow, surrounded on all sides by older rocks, the bottom of the basin being 270 feet deeper than the lowest part of its rim at Bingen. These deposits, however, are not lacustrine but fluviatile. Hence we must infer that fluviatile deposition has kept pace with the crustal movement. As the bottom of the Rhine valley has slowly subsided, the river has flowed on without interruption, continuously filling up the gradually deepening basin with its sediment.

CHAPTER XII

STRUCTURES RESULTING FROM DENUDATION

Outliers and Inliers. Unconformity. Overlap.

In preceding chapters, frequent reference has been made to denudation in explanation of certain constantly occurring phenomena. For example, it was necessary to point out that plutonic rocks are now visible at the surface simply because they have been bared or denuded by long-continued epigene action. The student who has followed so far must also have realised that the very existence of sedimentary rocks is evidence of denudation—for every bed of the kind has been derived from the breaking-up and disintegration of some pre-existing rock or rocks. Denudation and sedimentation, in short, go hand in hand. We cannot have the one without the other. In this chapter attention will be directed to certain rock-structures which may be said to owe their origin to denudation.

Outliers and **Inliers.**—All land-surfaces are necessarily subject to degradation, and the marks of such degradation or wearing-away are necessarily most conspicuous in regions which have been longest exposed to epigene action. Vast masses of rock have been gradually removed from such regions, so that many formations which formerly extended continuously over wide areas have been greatly reduced. Sometimes, indeed, they are now represented by only a few interrupted sheets and isolated patches. Such is the origin of outliers. An **Outlier**, then, is simply a relic of some more or less extensive bed, or series of beds, and may be shortly defined as a detached area of rock, surrounded on all sides by rocks which are geologically older than itself. Such being the case, outliers very often appear capping hills and ridges. They occur amongst all kinds of rocks, no matter how these may be arranged—whether they be horizontal, inclined, or highly flexed and folded. Examples are met with almost everywhere throughout these islands. They often appear scattered along the front of prominent escarpments, of which they are really the outposts, as may be seen in Fig. 64, which represents diagrammatically the outliers and escarpments of the Jurassic and Cretaceous strata of Central England. These outliers are obviously detached portions of the more durable strata, of which the escarpments are composed, and have been left behind, so to speak, during the slow retreat of the latter under the influence of denudation. Sometimes outliers owe their preservation not so much to the durability of their rocks, as to their relatively strong geological structure. Hence, not infrequently, outliers occur in synclinally arranged strata (Fig. 65, O). The rocks of which an outlier is composed may rest either conformably or unconformably on older strata (Fig. 65). The outliers of Torridon Sandstone seen in Plate XLVII. are separated from the underlying Archæan gneiss by a strong unconformity (see p. 183).

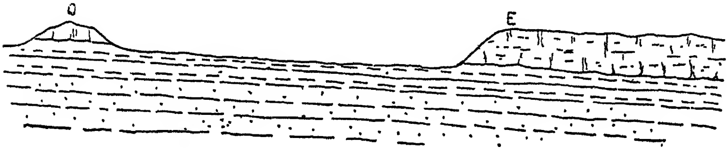


FIG. 64.—ESCARPMENT, E, AND OUTLIER, O.

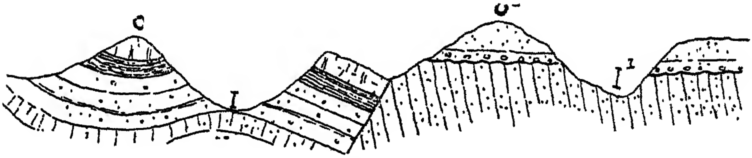


FIG. 65.—OUTLIERS (O) AND INLIERS (I) IN CONFORMABLE AND UNCONFORMABLE STRATA.

Although outliers usually occur on high-lying ground as the direct result of denudation, yet they occasionally owe their existence to faults, and in such cases they may appear either on heights or in depressions. Trough-faults, for example, necessarily bring down younger beds against older formations, and thus detached portions of strata are preserved—the rocks with which they were formerly connected having been entirely removed from the immediate neighbourhood.

An **Inlier** is the converse of an outlier, and consists of rocks which are surrounded on all sides by rocks which are geologically younger. The rocks of an inlier may belong to the same series as those by which it is surrounded (Fig. 65, I), or they may be overlaid discordantly by the latter (Fig. 65, I^1). As an inlier is the result of denudation, and due simply to the partial removal of overlying rocks, the structure is most frequently encountered in valleys and other depressions. Necessarily, however, inliers often appear along the backs of denuded anticlines, as in the case of the Carboniferous Limestone of Roman Camp Hill, near Edinburgh (Fig. 66, I). Faulting also sometimes accounts for the presence of an inlier forming elevated ground. For example, we occasionally encounter hills composed of ancient rocks rising more or less abruptly out of plains or plateaus consisting of younger formations. This is the structure of the "Horst mountains" of German geologists, the general characters of which are shown in Fig. 67. In this case it is obvious that the inlier represents a higher crustal level—the Horst owes its existence as such to the faults or dislocations by which it is bounded. An old plateau-land has been fractured—the tracts surrounding the inlier having broken away from it and dropped to a lower position.

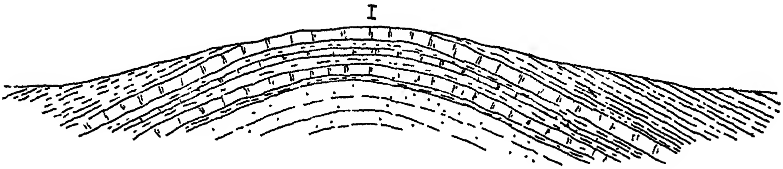


FIG. 66.—SUMMIT OF AN ANTICLINE FORMING AN INLIER.

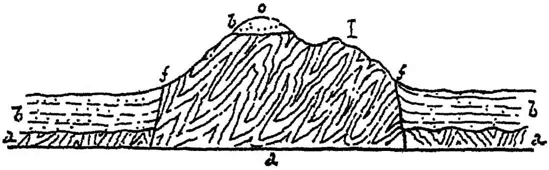
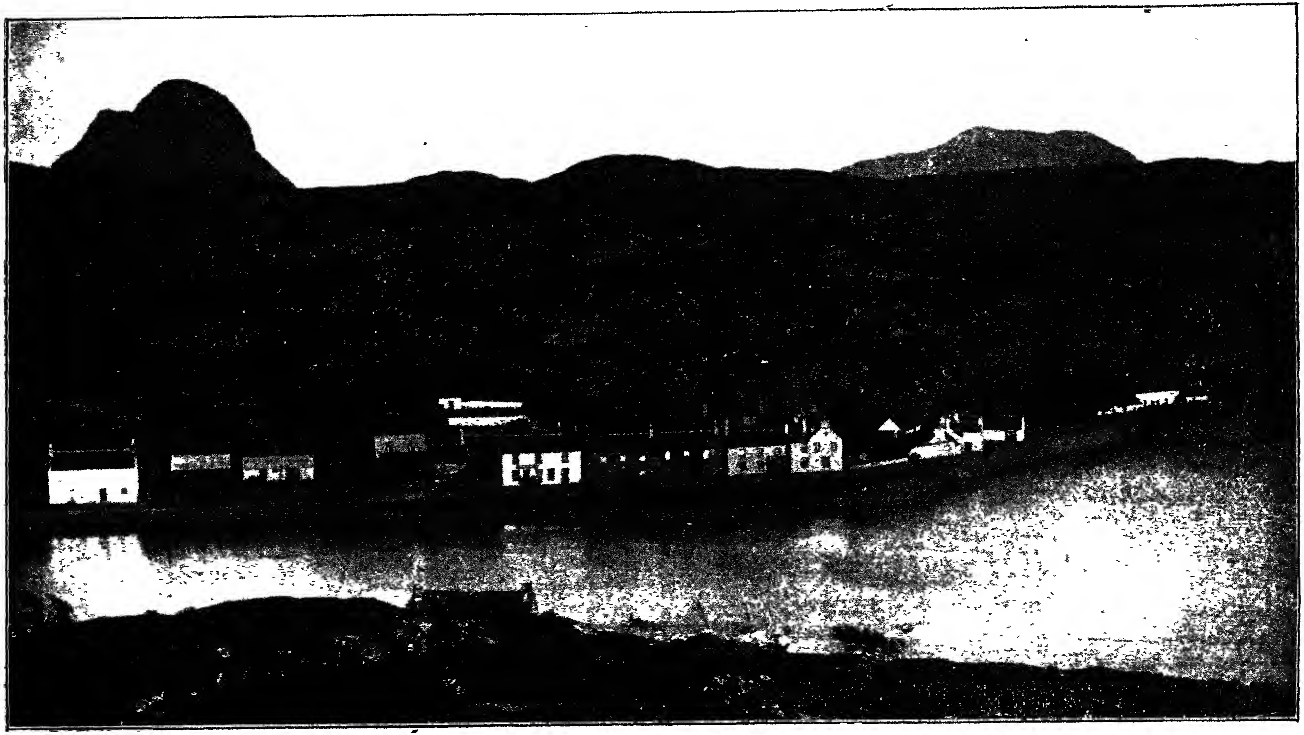


FIG. 67.—INLIER RESULTING FROM FAULTING.

a, schistose rocks; *b*, *b*, younger sedimentary strata; *f*, *f*, faults; *o*, outlier of *b*; I, inlier of *a*.

Conformity and **Unconformity.**—When one series of strata has been laid down upon the undisturbed and undenuded surface of another series, so as to form a continuous succession, the beds are said to be conformable—the structure

PLATE XLVII



Platform of Archæan Gneiss in Sutherland, with Outliers of Torridon Sandstone resting on it; Suilven to the left.

Photo by H.M. Geological Survey.

[*To face page* 183

being known as conformability or conformity. In a true **conformity,** therefore, each successive bed rests regularly upon its predecessor. When, on the other hand, one set of beds has been deposited upon the worn or denuded surface of another and older series, we have what is termed an **unconformity** or unconformability, and the two sets of beds are said to be unconformable with each other. Unconformity sometimes occurs without any change in the relative position of the younger and older strata. Both may be horizontal, or may dip at the same angle and in one and the same direction (Figs. 68, 69). In such cases (sometimes distinguished as *disconformities*) the lower series will usually afford evidence of having been more or less denuded before the deposition of the overlying series had commenced. Occasionally, however, such evidence of a physical break or interruption of sedimentation is hard to detect in individual exposures or sections. But when the strata are traced over some considerable area the actual discordance will be shown by the manner in which the upper gradually steals over the outcrops of the lower series. In cases of this kind the presence of an unconformity is often indicated by the occurrence of rolled or angular fragments of the lower rocks enclosed in the lowest bed or beds of the upper series. Indeed, conglomerate and grit frequently appear along every kind of unconformable junction. Again,

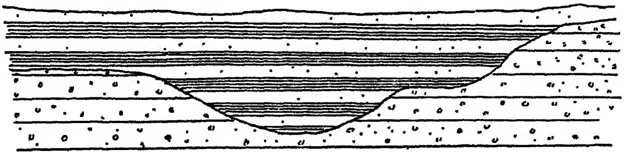


FIG. 68.—MARKED UNCONFORMITY IN HORIZONTAL STRATA.

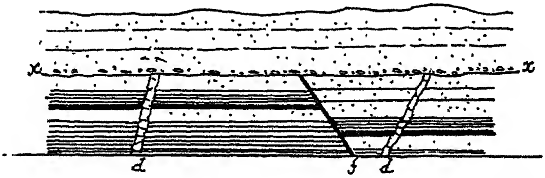


FIG. 69.—INCIDENTAL EVIDENCE OF UNCONFORMITY IN HORIZONTAL STRATA.

x, *x*, unconformable junction; *d*, *d*, dykes; *f*, fault.

the presence of dykes of igneous rock and dislocations in the lower series and their absence from the overlying beds—dykes and faults terminating abruptly at a given line of junction—would be convincing evidence of a "break in the succession" (see Fig. 69). For it is highly improbable that two or more dykes should terminate upwards at exactly the same level; while we may feel assured that if the dislocations visible in the lower beds do not extend into the overlying strata, the latter must be resting upon a denuded surface.

When none of these incidental proofs of unconformity is present, the evidence of fossils may yet be available. The assemblage of fossils occurring in the lower beds may be more or less strongly contrasted with that of the overlying series, and so lead to the conviction that the appearance of conformity is deceptive. Such an abrupt break in the continuity of life-forms is termed by palæontologists a "break in succession," and indicates a gap or imperfection in the record, which usually implies a long lapse of time. We must allow for the gradual extinction of the old forms of life occurring in the lower beds, and for the gradual introduction of the different series of types which appear in the upper beds. In short, the apparent conformity in such a case is deceptive—it is in reality an unconformity.

Usually, however, unconformity is marked by some discordance of inclination—one set of beds often resting upon the upturned and denuded edges of an older series (see Figs. 70, 71 and Plates XLVIII., LXI.). Thus the lower beds may be inclined and the overlying strata horizontal; or both may be inclined in the same or in different directions. Strongly marked discordances of this kind are not hard to trace, even when there is no section to show the actual junction of the two sets of strata.

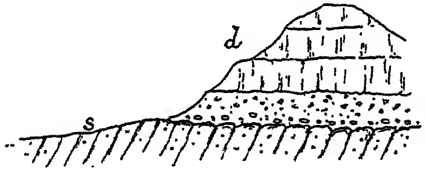


FIG. 70.—STRONG UNCONFORMITY.

Conformity, as a rule, indicates more or less continuous sedimentation or accumulation—a persistence, upon the whole, of the same physical conditions. It does not, however, prove that the area of deposition was stable. On the contrary, a thick series of conformable strata of shallow-water origin could only have been accumulated during gradual subsidence of the area. The evidence supplied by palæontological "breaks in the succession" further shows that the accumulation of apparently conformable strata has sometimes been interrupted for prolonged intervals of time. But these are really cases of unconformity, and do not invalidate the general rule that true conformity indicates a persistence of the same physical conditions.

It must be remembered, however, that conformable strata have not necessarily accumulated during one continuous movement of subsidence. As already pointed out (see p. 111), both downward and upward crustal movements may take place during the deposition of a long series of perfectly conformable strata, and these changes may sometimes lead to longer or shorter pauses in the process of accumulation. While, therefore, it holds generally true that conformity is the result of more or less continuous sedimentation, we must allow for such interruptions of the process as those discussed in Chapter VII.

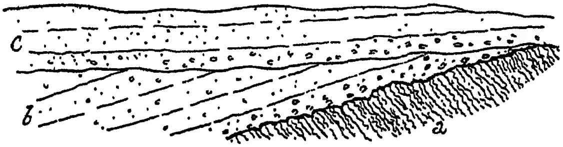


Fig. 71.—Two Unconformities.

Unconformity, on the other hand, obviously implies an interruption of sedimentation or accumulation, and the supervening of erosion and denudation—or, in other words, a change of physical conditions. In short, unconformity points usually to the following succession of changes: (1) a period of accumulation—either lacustrine or marine; (2) a crustal movement resulting in the conversion of the area of sedimentation into dry land; (3) a more or less prolonged period of erosion, during which the land surface is denuded; (4) renewed subsidence and deposition of younger accumulations over the worn and irregular surface of the now drowned land; (5) final re-elevation of the area.

Overlap.—When the upper beds of a conformable series extend over a wider area than the lower beds of the same series, we have the structure known as overlap. The structure indicates subsidence accompanied by sedimentation over a gradually extending area, and overlap is therefore often well displayed in cases of marked unconformity. In the accompanying section (Fig. 72), for example, the older rocks, *a*, have been much eroded, so that when submerged they formed a very irregular sea-floor. The hollows being gradually filled with sediment, *b*, it is obvious that the upper must overlap the lower beds—each stratum extending over a wider area than its predecessors. But overlapping must take place in every case of the gradual subsidence of land, whether the surface of the sinking area be irregular or relatively smooth. As the land sinks, shore-deposits become overlapped by infra-littoral deposits, and these last by the accumulations of deeper water.

Overlap is a structure which is not only interesting and instructive to the geologist, but it has also an obvious practical bearing. In questions of boring for bedded minerals it is often of the utmost importance, and failure to recognise the structure has led to disappointment and loss which might have been avoided. Similarly, in questions of water-supply, the possible occurrence of overlap and unconformity cannot be safely disregarded.

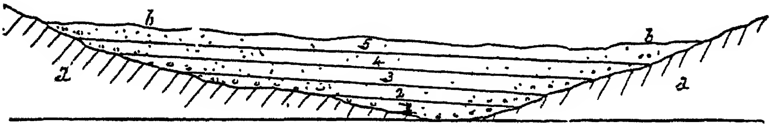
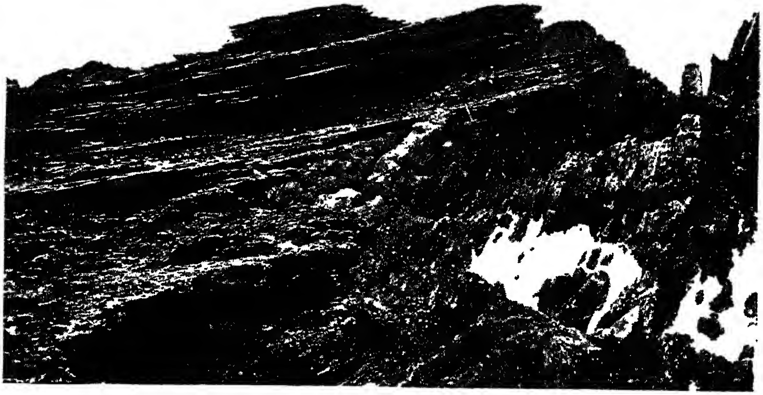


FIG. 72.—UNCONFORMITY AND OVERLAP.

Transgression and **Regression.**—When gradual subsidence has affected a very extensive area—(possibly of continental dimensions)—overlap is developed on a grand scale—one great geological system often stretching for hundreds of miles beyond the limits reached by the immediately preceding system. Overlap on this grand scale is termed *Transgression*, and the geological period during which it took place is spoken of as a *period of marine transgression*. Should such a movement of depression be succeeded by gradual re-elevation of the sunken tract the process of overlapping will be reversed, and sedimentation will take place over a progressively diminishing area. In this case, the latest deposits will have the most restricted range. This is termed *Regression*.



1. Siccar Point, Berwickshire. Unconformity between gently-inclined Upper Old Red Sandstone and vertical Silurian beds.

Photo by T. C. Day.

2. Polneul Burn, Sanquhar. Unconformity between Upper Carboniferous and Ordovician.

Photo by A. G. Stenhouse.

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CHAPTER XIII

ERUPTIVE ROCKS: MODE OF THEIR OCCURRENCE

Intrusive Eruptive Rocks. Plutonic or Abyssal and Hypabyssal Rocks—their General Petrographical Characters. Subjacent Masses—Batholiths, Stocks, Bosses. Mode of Emplacement of Batholiths. Injected Masses—Laccoliths, Sills, Lopoliths, Phacoliths; Dykes and Veins; Ring-dykes and Cone-sheets.

IGNEOUS rocks have either been extruded at the surface, as in the case of volcanic eruptions, or they have cooled and consolidated below ground, and are now exposed to the light of day owing to the removal by denudation of the rock-masses underneath which they formerly lay concealed. We have thus two types of eruptive rocks, namely, effusive and intrusive, the latter of which is most conveniently described first.

INTRUSIVE ERUPTIVE ROCKS

These rocks are sometimes termed **subsequent,** with reference to the fact that they are of subsequent origin to the rock-masses with which they are associated. Two groups of intrusive rocks are recognised, namely, (*a*) **Plutonic** or **Abyssal,** and (*b*) **Hypabyssal** rocks, the former having consolidated at great depths in the crust, while the latter are of less deep-seated origin. It must be admitted, however, that no clear line of demarcation separates these two groups—the one type of rock passing into the other. Nevertheless, the extremes of the two series are more or less strongly differentiated by their petrographical characters, and also to some extent by the mode of their occurrence.

The Plutonic or more deeply-seated rocks are never vesicular or slaggy and contain no glass. Moreover, they are usually rather coarsely crystalline and generally granitoid in texture. Their constituent minerals are often crowded with fluid-cavities, while glass- and stone-cavities are wanting. The Hypabyssal or less deeply-seated rocks occasionally exhibit all these characters, but they also not infrequently contain sporadic areas of vesicles, and even, it may be, some residual glassy base or devitrified matter. Although often coarsely crystalline, they commonly assume a fine-grained and sometimes a compact texture. Hypabyssal rocks thus frequently have a strong resemblance to effusive or lavaform rocks, from which, indeed, it is often quite impossible to distinguish them in hand specimens. The contrast between these two types is consequently much less marked than that between plutonic rocks and true lavas. Even in hand specimens a truly plutonic or abyssal rock can rarely or never be confounded with one which has flowed out at the surface and consolidated under the ordinary pressure of the atmosphere.

The true character of an igneous rock, however, can only be satisfactorily determined by studying it in the field and observing its relation to the other rock-masses amongst which it occurs. Usually it is not difficult to recognise an intrusive rock, since its junction with surrounding rock-masses is generally more or less irregular and often highly discordant. Many observations in all parts of the world have shown that molten matter invading the crust from below has usually followed what may be considered lines of weakness. That crust, as we have now learned, is by no means homogeneous, but built up of a great variety of rocks arranged in many different ways, and traversed by an infinity of regular and irregular cracks, fissures, rents, and dislocations, many of which are vertical or approximately so, while others are inclined at all angles. All such original and superinduced planes of division—whether planes of bedding, cleavage, or foliation, whether unconformable junctions, joints, or faults—are lines of weakness along which molten matter has from time to time found more or less ready passage to the surface. Further, it may be noted that molten matter has not infrequently made a way for itself by fusing or dissolving and absorbing certain rocks, such as coal and limestone, and even much less readily reduced materials.

It is obvious, therefore, that molten masses which have cooled and consolidated within the earth's crust must vary in shape according to the form of the passages and cavities which have been opened for them. Consequently, from the point of view of tectonic geology, intrusive eruptive rocks are grouped under certain more or less definite structural types.

It must not be supposed, however, that each individual intrusive mass necessarily belongs wholly to one or other of these typical structures. Transitions must occur, and not infrequently, as we shall learn, several different types may be represented by one and the same eruptive rock-mass.

Daly has distinguished two main categories of intrusive bodies, namely **Subjacent Masses** and **Injected Masses.** The former, although clearly intrusive, are not visibly floored; typically they enlarge downwards to some unknown limit. The latter, on the other hand, are completely enclosed by the rock formations they have invaded except along the relatively narrow feeding channels. Subjacent masses include *Batholiths*, *Stocks* and *Bosses*. Injected masses belong to two contrasted groups:—(*a*) Concordant Injections, where intrusion has taken place along planes of stratification or schistosity, and (*b*) Discordant Injections, where it has occurred across those planes. Concordant injections include *Laccoliths*, *Lopoliths*, *Phacoliths*, and *Sills*. The more important discordant injections are *Dykes* and *Veins*, *Ring-dykes*, *Cone-sheets*, and *Volcanic Necks*.

1. SUBJACENT MASSES

The term **Batholith** is applied to intrusive masses of deep-seated origin, which seem to occupy amorphous or irregular-shaped cavities, usually of large dimensions, often indeed measuring several miles in diameter (Fig. 73). Batholiths are found, for the most part, in orogenic belts and are generally elongated parallel to the tectonic axes of the mountain-ranges. The junctions with the roof of country rock are highly irregular, " pendants " of the latter projecting downwards into the igneous mass, protrusions of which in pipe-like form may appear at the outcrop as apparently detached " cupola-stocks." Downward enlargement of batholiths, in some cases for distances of thousands of feet, has been

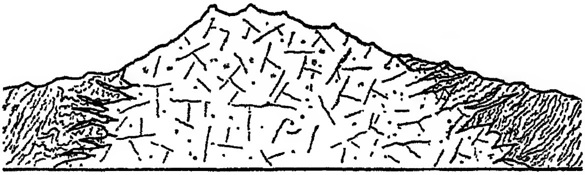
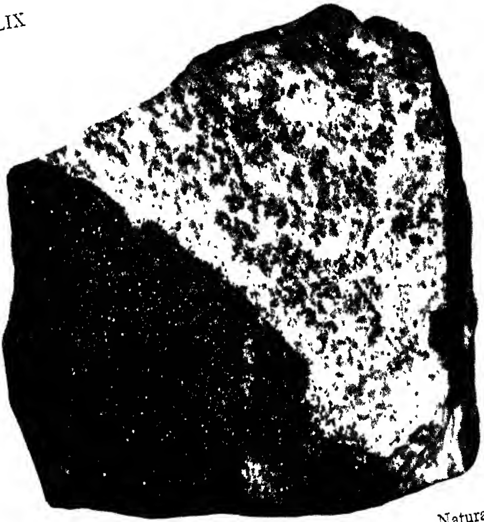
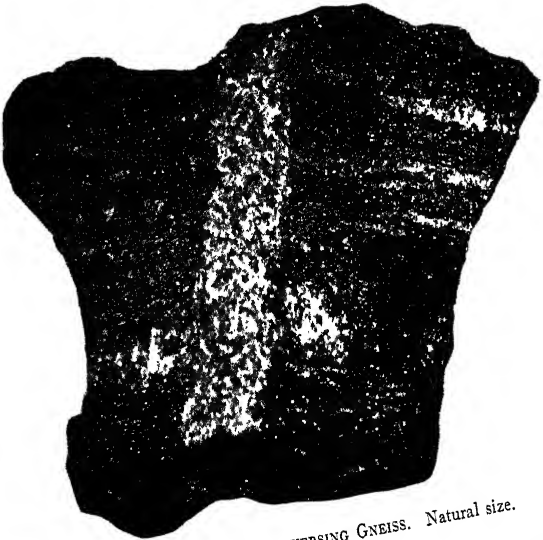


FIG. 73.—DIAGRAMMATIC SECTION ACROSS A BATHOLITH.

PLATE XLIX



1. JUNCTION OF GRANITE WITH FINE-GRAINED GNEISS. Natural size.



2. VEIN OF GRANITE TRAVERSING GNEISS. Natural size.

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demonstrated by direct observation of contacts in deep valleys and in mining operations; it can be inferred also from the distribution of satellitic stocks and from studies of aureoles of contact metamorphism. In most cases they consist of "granitic" rocks—granites, quartz monzonites, and granodiorites.

The petrographical character of granitic rocks, not less than the phenomena presented by the rocks they traverse, are sufficient proof of their deep-seated origin. Granitic intrusions range in age from the oldest period recognised by geologists down to Tertiary times. By far the larger number, however, date back to Palæozoic and Archæan ages—very few, indeed, being referable to Mesozoic and Cainozoic horizons. From this we are not justified in concluding that intrusions of granite were of more common occurrence in the earlier than in the later stages of the world's history. Granite, being of plutonic origin, can only appear at the surface as the result of long-continued and profound denudation, and its relative age is fixed by that of the rocks it traverses. If the surrounding rocks be of Palæozoic age, all we can say is that the intrusion is of later date than these—but how much later we cannot tell. For, obviously, much denudation must have taken place before the granite could become exposed at the surface. It may originally have risen to a much higher geological horizon—all evidence of this having been destroyed by the complete removal of the overlying younger rocks, and those portions of the batholith itself by which these may have been penetrated. As every granite intrusion must in this way have traversed older rocks before it could reach superincumbent younger rocks, we might have expected to find batholiths most frequently associated with the former, although many may really belong to a much later date.

Collateral evidence sometimes enables the geologist to fix the approximate age of a batholith. When, for example, the rock is seen traversing Carboniferous strata, while fragments of it are enclosed in beds of early Permian age, we may infer that the intrusion probably took place towards the close of Carboniferous times.

Along its junction with adjacent rocks, granite is often finer grained than elsewhere in the same mass, as if the molten magma had become chilled by contact with its surrounding walls, and cooled too rapidly to allow the constituent minerals to attain fuller development (see Plate XLIX. 1). Not infrequently, however, the rock is as coarsely crystalline along its margin as towards the centre of the mass. In such cases we may suppose that the surrounding rocks were so highly heated as to have no chilling influence. Although the junction between granite and the rocks invaded by it is usually so clearly defined that a knife-edge may be laid upon it, yet this is not always the case. Occasionally, the eruptive rock seems to merge insensibly into the other, and no line of demarcation is visible. Again, it sometimes happens that when granite has invaded schists or slates it has penetrated these by a kind of leaf-by-leaf injection—the liquid rock having insinuated itself in excessively thin sheets and veins along planes of foliation or cleavage. Under such conditions the invaded rocks are so intimately mixed with granite and so highly metamorphosed, that it is often very difficult to distinguish between them and the invading rock. The alternating leaves of granite and schist combine, in short, to produce a rock which has the aspect of a gneiss into which the granite-mass seems, as it were, to graduate.

Now and again the marginal area of a granitic batholith contains more or less numerous angular and subangular fragments, slabs, reefs, and blocks of schistose or other rocks. Such inclusions, or **xenoliths**, as they are called, have been torn from the rocks abutting upon the granite and enclosed in it at the time of its intrusion. It may be added that granitic batholiths not infrequently show a kind of foliated or flow structure near their margins—the constituent minerals being arranged roughly parallel to the junction-line. This may indicate an actual fluidal movement, or it may simply be the result of hydrostatic pressure, exerted by the mass of the granite itself.

The much smaller intrusive bodies known as **Stocks** and **Bosses** resemble batholiths in all essential features except size. The term " boss " is generally restricted to those which appear nearly circular in ground-plan.

Batholiths appear to rise vertically as if they occupied enormous pipes or funnels. Yet there is little reason to doubt that most large masses of granite and granodiorite never had any communication with the surface, but cooled and consolidated at abyssal depths. The mode of emplacement has been the subject of much discussion and speculation. Apart from

PLATE L

COLUMNAR JOINTING IN SILL, DRUMADOON, ARRAN. [Quartz-porphyry intruded among Triassic strata.]

Photo by H.M. Geological Survey.

[*To face page* 193

occasional evidence of doming of the roof region, there is little or no appearance of the surrounding rocks having been pushed aside to make room for the eruptive masses. Current views favour the melting of the deepest portion of the so-called granitic layer of the earth's crust as the prime factor in their origin. Such melting would be likely to take place only when orogenic movements, leading to a tectonic thickening of the crust, brought about a sufficient steepening of the thermal gradient. The generation of magma, *palingenesis*, by large-scale fusion of the granitic layer, in part by pure melting, in part by the aid of the solvent action of granitic liquid and hot plutonic gases from magma in depth, was advocated strongly by Sederholm. Daly has stressed yet another factor as of importance in the making of room for the ascent of the granitic magmas of batholiths—the process which he has termed *magmatic stoping*. This may occur on both a major and a minor scale. In the former case one may picture that, during orogenic disturbances, there may have been a breaking-apart of relatively large sections of the crust, which foundered in the palingenetic magma formed by the melting process—to be incorporated in the latter, perhaps by assimilation. In the case of minor stoping, of which there is ample proof in the higher parts of batholiths, there is often clear evidence of fracturing of the roof and walls. When the fragmentation has taken place at a late stage in the cooling history, the fragments appear as xenoliths in the intrusive rock. Since, however, in most cases the xenoliths are heavier than the magma, they will at earlier stages have sunk and in all probability have been assimilated.

It must not be supposed that granite always occurs in batholiths, stocks, or bosses. On the contrary, it frequently appears in the form of extensive sheets of very variable thickness and, as we shall see later, as *ring-dykes*—and it may well be doubted whether many of the plutonic masses which have been supposed to occupy more or less vertical funnel-like cavities are really of this character. So far as one can tell from what is exposed at the surface, the so-called " bosses " may simply be partially exposed sheets, some of which, however, must have a thickness of several thousand feet. A sheet-like structure is suggested by the fact that, far removed from the margin of a granite area, inliers of the same rock are not infrequently revealed in the beds of streams which have cut their way down through a great thickness of the metamorphosed rocks surrounding the central mass. In such cases the granite may either be of the nature of a laccolith, or thick sill or sheet, following an irregular course through the rocks among which it has been intruded (Fig. 74), or the central mass may be a true boss from which sheets extend outwards at different levels and in different directions (Fig. 75).

The rocks for some distance around a mass of granite are usually more or less highly metamorphosed, as will be more fully explained in the sequel.

Large batholiths, as we have seen, are composed usually of acid plutonic rocks such as granites and granodiorites, less frequently of quartz-diorite or syenite. Stocks and bosses, on the other hand, show much greater diversity in composition, consisting sometimes of the above rocks but very frequently also of types such as gabbro, quartz-gabbro, norite, nepheline-syenite, etc. From subjacent intrusions of all kinds proceed more or less numerous apophyses—sheets or sills, dykes, and veins—which penetrate the contiguous rocks often for considerable distances.

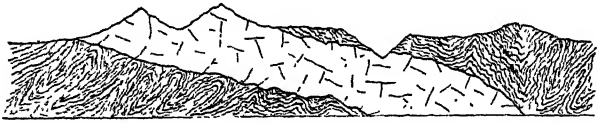


FIG. 74.—GRANITE SILL OR SHEET.

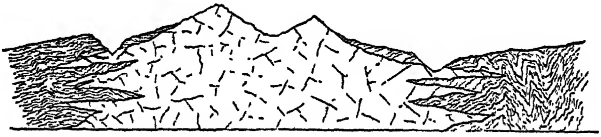


FIG. 75.—GRANITE BATHOLITH SENDING OUT SILLS.

2. CONCORDANT INJECTED MASSES

The name **Laccolith** has been given to certain remarkable masses of intrusive rock, which were first described by Gilbert as occurring in the Henry Mountains of Southern Utah. The same type of structure has since been recognised in the Elk Mountains, and elsewhere in North America. As these laccoliths are of late Tertiary age, many of them are still in an excellent state of preservation, and the phenomena they present enable us to understand more readily the conditions under which certain of our own intrusive rock-masses may have come into existence. The general structure of a laccolith is illustrated in the accompanying diagram (see Fig. 76). It will be observed that the intrusive rock is lenticular in shape, that it sends out sheets, dykes, and veins into the contiguous strata, and is in connection with a subjacent dyke-like feeder. According to Gilbert, the molten rock has risen through this vertical fissure, but, being unable to burst across the superincumbent beds, has insinuated itself between the strata, lifted these up, and thus produced a dome-like elevation at the surface. Proceeding from such a laccolith are more or less numerous intrusions—some of which have been injected along the bedding-planes, while others cut across the fissured strata at all angles. While laccoliths sometimes occur singly, they more usually appear in clusters—the presence of each cluster being indicated by a dome-shaped mountain. The number of individual laccoliths in a cluster is variable—sometimes there are no more than two, in other cases there may be a score, the largest number recognised in one group being thirty.

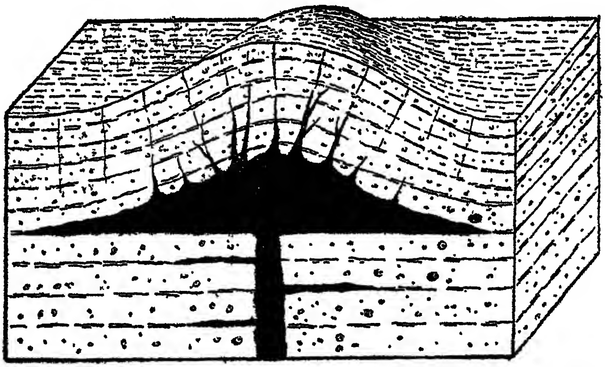


FIG. 76.—LACCOLITH.

Let us now see what light this American type of intrusive rock throws upon the phenomena of the sills or intrusive sheets which are of such common occurrence in our own country. **Sills** (Plates L., LI.) are eruptive masses which have usually been intruded along planes of stratification, and hence they tend to assume a more or less regularly bedded aspect. The plane along which intrusion has taken place is not necessarily, however, a plane of bedding. Some sills have followed planes of slaty cleavage and foliation, while others continue for longer or shorter distances along lines of fracture. But certainly the most typical examples are met with amongst stratified rocks, with which they have the appearance of being interbedded. Almost any kind of eruptive rock may assume the form of a sill, although the deeper seated granitoid rocks, such as granite, syenite, etc., appear less frequently in sheet-like masses than the hypabyssal dolerites, teschenites, quartz-porphyries, etc. Perhaps the most typical examples of the true sill are those which occur so frequently among the Palæozoic strata of these islands—the sills of the Carboniferous areas being particularly well known. It may suffice, therefore, to give a short account of the latter.

We may note, then, that a sill, although it may seem to be interbedded as a member of one consecutive series of strata, does not exactly conform to the immediately overlying and underlying beds (Fig. 77). Followed along the outcrop, it is found now and again to leave the plane upon which it first appeared—either rising to a slightly higher or descending to a slightly lower level. Or it may suddenly break across a considerable thickness of strata and proceed thereafter along a totally different horizon. Not infrequently it contains fragments torn from the contiguous rocks; occasionally, indeed, large slabs or sheets of the invaded strata have been caught up and enclosed in the eruptive rock, and such fragments are invariably much baked and altered. Many thick sills divide into two or several subordinate sheets, each more or less closely following a plane of bedding. Often, also, dykes and veins proceed from sills into the adjacent rocks. This is frequently the case when a thick sill divides, the separate sheets being often connected by one or more dykes passing across the intervening strata. But the whole complex of sheets and dykes has obviously been intruded at one and the same time. Each independent sill or group of subordinate and associated sheets is doubtless connected with one or more vertical pipes or feeders, although these have not often been seen in section.

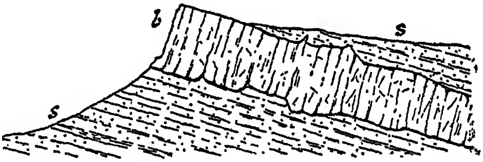
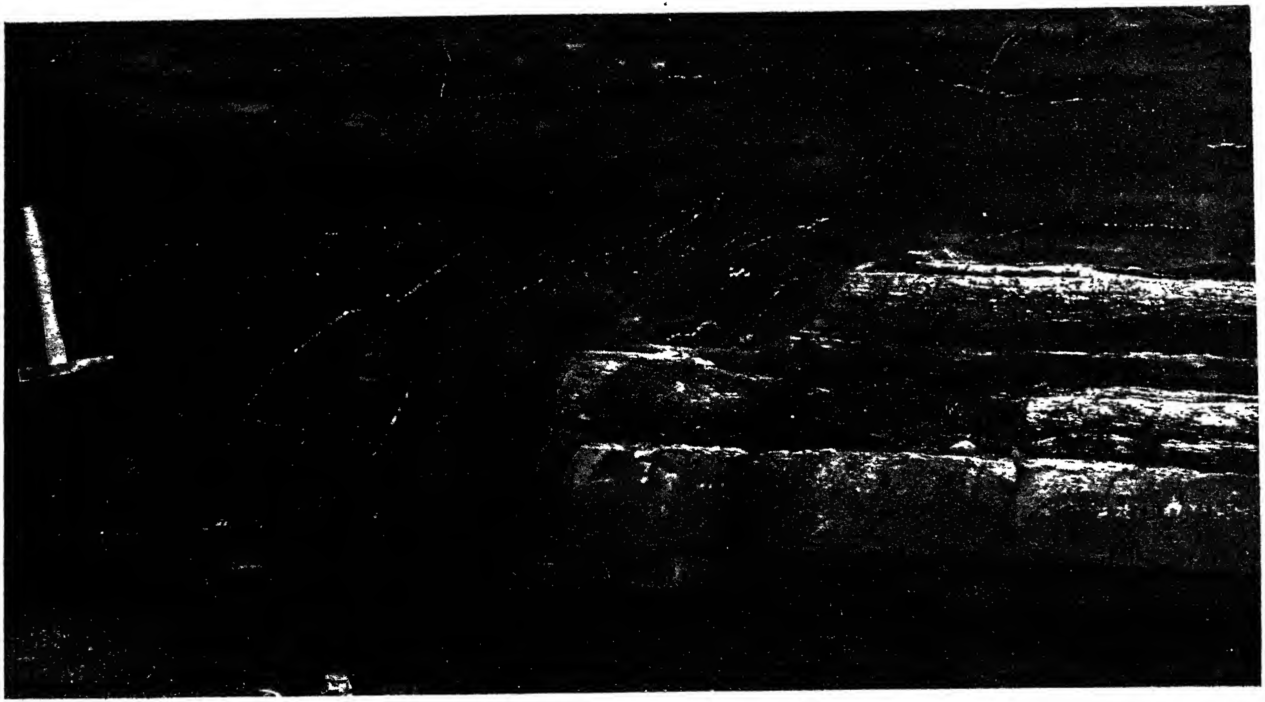


FIG. 77.—SILL OR INTRUSIVE SHEET.
b, dolerite; *s*, sandstones and shales.

PLATE LI



Sill (Dolerite) cutting across Sedimentary Strata, Shore, near Kinghorn, Fife.

Photo by H.M. Geological Survey.

[*To face page* 197

The sills of our Carboniferous areas consist principally of basic rocks, mainly olivine-dolerites, teschenites, and quartz-dolerites. Some of these are not more than a few feet or yards in thickness ; others may reach and even exceed 150 feet. They are all lenticular in shape, some dying out more rapidly than others. At and near its junction with the overlying and underlying strata, a sill is almost invariably finer grained than towards the centre of the mass. Along the actual line of contact it is frequently compact and even markedly vitreous. In the case of thin sheets the texture is usually finer grained, and the rock may contain much glassy base throughout. The thicker sills, on the other hand, tend to be coarser grained and holocrystalline. Vapour cells are usually absent, although now and again sporadic areas of vesicles appear; but these are never so plentiful as to impart a scoriaceous aspect to the rock.

Where basic sills and dykes have traversed carbonaceous rocks, such as coals and oil-shales, the igneous rock is often highly altered, assuming a white or yellowish-white colour. Such "bleached" dolerites and basalts are known locally as *white trap* (Plate LV.). In thin slices of these rocks it can be seen that the outlines of the primary minerals and the usual textural features are retained, but that the original mineral substances have been replaced by aggregates of carbonates of lime, magnesia and iron, kaolin and muscovite. The rocks apparently crystallised in normal fashion, but, after the temperature had fallen sufficiently, the primary silicates were completely altered by the action of CO_2 and other gases produced from the destructive distillation of the carbonaceous rocks.

The strata in contact with a sill never fail to afford evidence of having been subjected to the action of heat. Both overlying and underlying strata are invariably affected, the alteration at the point of contact being often excessive. But the alteration never extends so far from the eruptive rock as in the case of granitic intrusions. Some account of these and other changes produced by sills will be considered in the sequel.

Sills often appear in large numbers in regions of former volcanic activity. Those associated with the Carboniferous strata of Scotland are a case in point—for volcanic action was manifested in that country again and again during Carboniferous times. It is probable, therefore, that most of the sills referred to were contemporaneous in origin with the lavas and tuffs of that period. Some of them may have been intruded before the eruptive forces had succeeded in establishing any communication with the surface; others may well be synchronous with the full development of volcanic activity; while yet others may mark the dying out of that action, when the eruptive energy was insufficient to pump magma to the surface. The out-cropping of these sills is, of course, the result of the general folding and denudation of the strata. But no one who compares the phenomena they present with those exhibited by the well-preserved laccoliths of North America can doubt that the older and younger structures have much in common, and may well have had the same origin. Sills which crop out at the surface so as to form lofty mural escarpments have been proved in many cases to wedge out downwards, and now and again their " feeders " have been recognised. In such cases it is not hard to reconstruct the original condition of the intrusion (Fig. 78). Indeed, it may be said that most of the salient features of the American laccoliths are reproduced by the sills of our own country. The latter occur singly or in groups just as the former do. A laccolith may divide, as it were, into two or more wedge-shaped and approximately parallel sheets, and many Scottish sills behave in the same way. So again from laccoliths and sills alike veins and dykes are protruded into the contiguous strata. There is evidence, moreover, in the tilting of the overlying strata that would lead us to infer that the Scottish sills in some cases may have affected the configuration of the surface, forming dome-shaped elevations in the same way as the laccoliths of the Henry Mountains. A good illustration is Traprain Law, near Haddington (see Plate LII.).

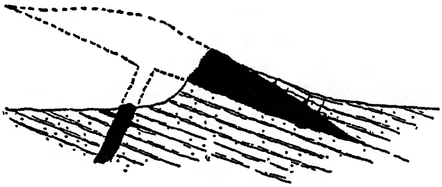
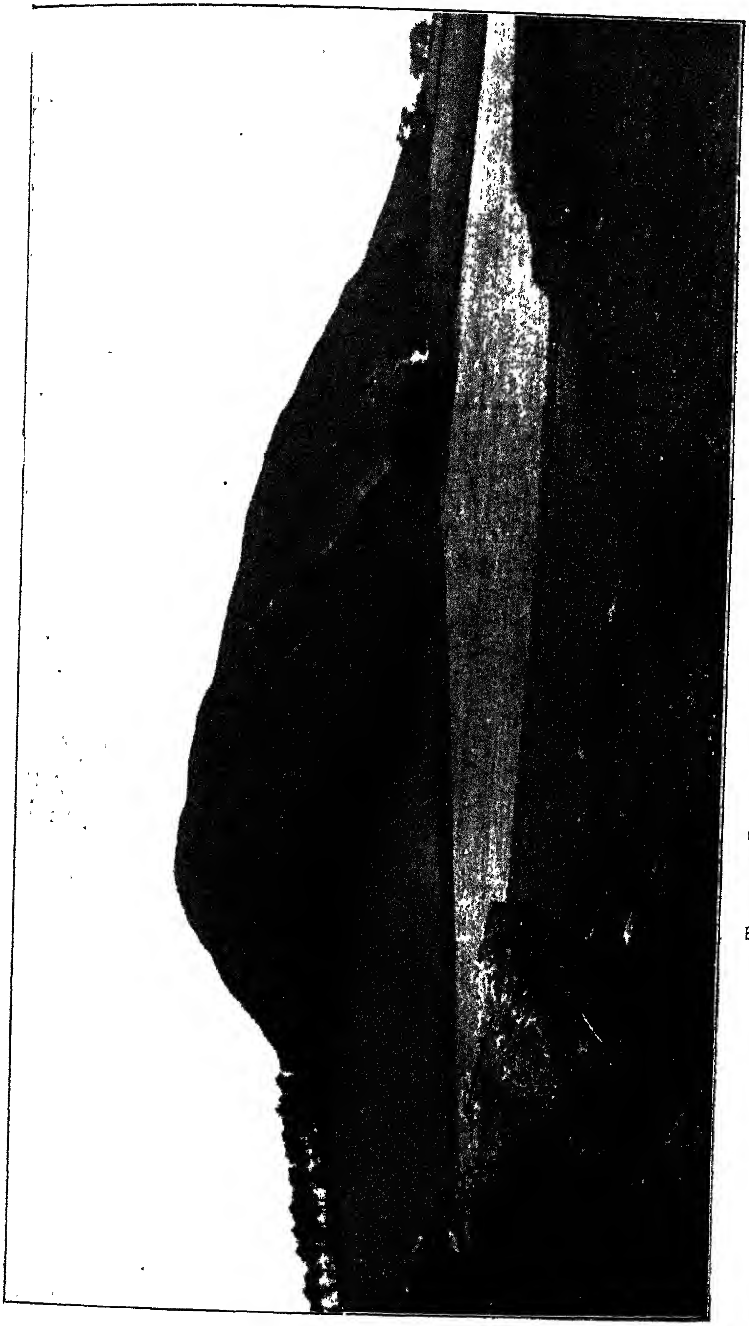


FIG. 78.—DIAGRAM OF A SILL, SHOWING ITS FORMER EXTENSION AS A LACCOLITH.

Composite Sills are usually defined as compound intrusions having the habit of sills but consisting of successive injections of more than one kind of magma. Such intrusions are very common in Scottish Tertiary volcanic districts. Thomas and Bailey, however, have suggested that the term should be restricted to cases where the later members do not show chilled contacts against the earlier. **Multiple Sills,** which are much less common, are the result, according to the usual definition, of successive injections of the same or closely similar magmas. Thomas and Bailey, on the other hand, use the term " multiple " for all cases where the later injections are chilled against the earlier, even if the successive magmas are dissimilar.

Among concordant injections may be included also **Lopoliths** and **Phacoliths.** Lopoliths, according to Grout who invented the term, are " large, lenticular, centrally sunken, generally concordant intrusive masses, with their thickness approximately one-tenth to one-twentieth their width or diameter." The type example is the Duluth gabbro of the Lake Superior region. In the case of laccoliths and lopoliths the igneous intrusion is the cause of the attendant folding. Harker directed attention to another type of intrusion, to which he gave the name of " phacolith," where the intrusion



TRAPRAIN LAW, EAST LOTHIAN. Outcrop of a Laccolith.

Photo by H.M. Geological Survey.

[*To face page* 198

is rather a consequence of the folding. Phacoliths are lens-shaped intrusive bodies found associated with folded strata and occupying the crests and troughs of folds, places where there is relief of pressure and a tendency to opening-out of the bedding planes.

3. Discordant Injected Masses

Erupted matter which has solidified in a more or less steeply inclined or vertical and somewhat even-sided fissure, is called a **dyke,** while the term **eruptive vein** is usually reserved for the more irregular and frequently tortuous and branching intrusions. But this usage is not invariable—many geologists employ the terms interchangeably, while others designate as " dykes " all the larger intrusions, whether wall-like or tortuous, and restrict the term " vein " to the smaller injections.

Eruptive veins and dykes may consist of almost any kind of igneous rock. Frequently they proceed visibly from large masses of eruptive rock—bosses or sheets, as the case may be. At other times no such relationship can be observed, although we can hardly doubt that if dykes and veins could be followed downwards they would be found to proceed in the same way from larger masses of intrusive character.

Wall-like intrusions are of common occurrence in this country—the most notable examples being the remarkable dykes of Tertiary age which are so abundantly developed in Western Scotland (see Fig. 79 and Plate LIII.). Dykes injected at different geological periods in the same region, it has been found, usually trend in different directions. Thus the Tertiary dykes shown in the figure have a dominant north-westerly trend, while the dykes of Permo-Carboniferous age, which are so abundantly developed in Central Scotland, trend in an east and west direction. Frequently, too, the dykes belonging to some particular era are clustered in linear groups or **swarms,** which can be related to contemporary plutonic centres. Such grouping is seen in the figure in the case of the Skye, Mull, and Arran swarms. The extraordinary abundance of dykes in the vicinity of plutonic complexes should also be emphasised. Detailed mapping has shown, for example, that 375 dykes occur in a breadth of 12·5 miles in the Mull swarm, and 525 dykes in a breadth of 14·8 miles in the Arran swarm. Only a very small proportion of these can be shown on a small-scale map such as that of Fig. 79.

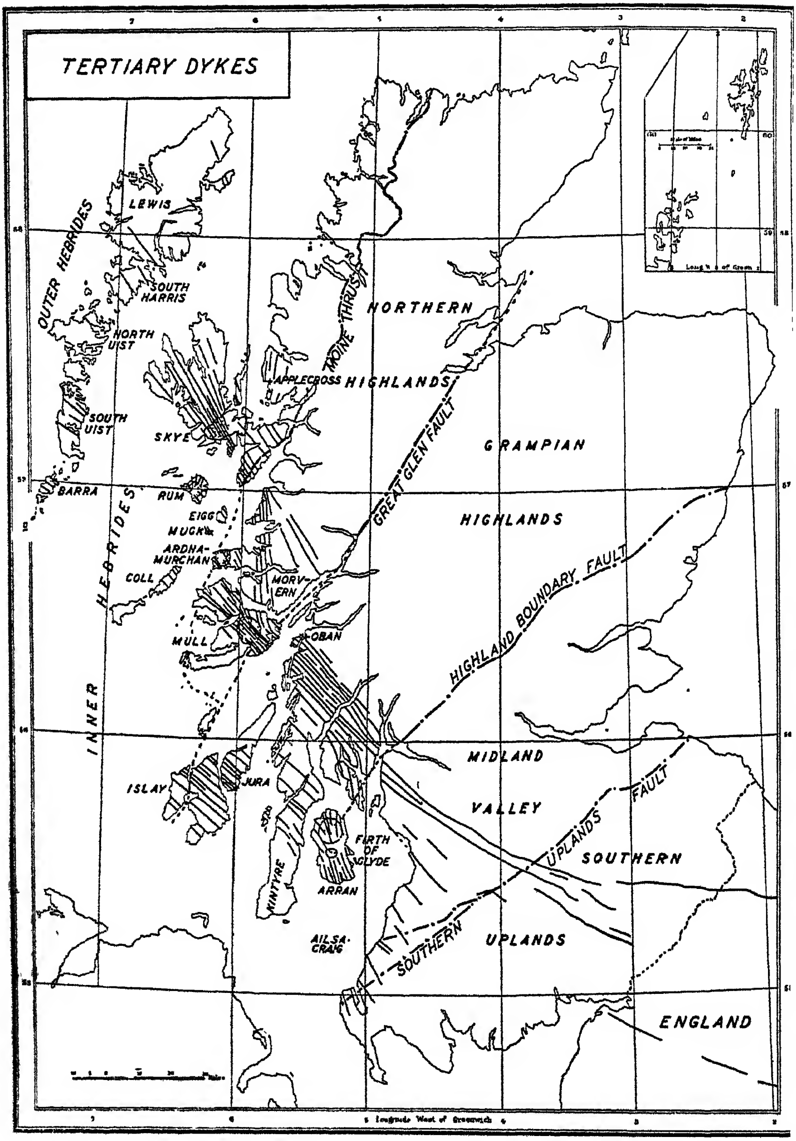

TERTIARY DYKES
7
6
5
4
3
2
58
57
56
55
LEWIS
OUTER HEBRIDES
SOUTH HARRIS
NORTH UIST
SOUTH UIST
SKYE
APPLECROSS
MOINE THRUST
NORTHERN
HIGHLANDS
GREAT GLEN FAULT
GRAMPIAN
HIGHLANDS
BARRA
RUM
EIGG
MUCK
ARDNAMURCHAN
COLL
INNER HEBRIDES
MORVERN
MULL
OBAN
HIGHLAND BOUNDARY FAULT
MIDLAND
VALLEY
ISLAY
JURA
KINTYRE
FIRTH OF CLYDE
ARRAN
AILSA CRAIG
SOUTHERN UPLANDS FAULT
SOUTHERN
UPLANDS
ENGLAND
Longitude West of Greenwich

FIG. 79.—TRENDS OF TERTIARY DYKES. AREAS OF TERTIARY PLUTONIC COMPLEXES ARE SHOWN BY STIPPLE. THE DYKES ARE USUALLY MUCH MORE NUMEROUS THAN INDICATED. FOR EXAMPLE, IN THE CASE OF THE MULL AND ARRAN SWARMS, WHERE THICKEST ONLY, ABOUT 2·5 PER CENT. AND 1 PER CENT. RESPECTIVELY OF THE KNOWN DYKES ARE SHOWN. (After J. E. Richey, *Trans. Edin. Geol. Soc.*, vol. xiii., 1939, p. 421.)

Dykes very often give rise to conspicuous surface-features—forming, as the case may be, either prominent ridges or elongated depressions, according as the dyke or the rock it traverses has offered the stouter resistance to denudation. When the former is the case, a dyke may rise wall-like above the general level of the country, continuing its course uninterruptedly for a longer or shorter distance across hill and dale. When, on the other hand, the rocks it cuts are more resistant than itself, a dyke indicates its presence by a long narrow trench or depression instead of a prominent ridge. The course followed by a dyke is, as a rule, remarkably straight or direct, though often gently sinuous. Occasionally, however, this regularity may be interrupted by one or more zig-zags or sharp bends. It is noteworthy that dykes which traverse sandstones and shales are usually straighter or more regular than those which cut through greywackés, crystalline igneous rocks, and schists. While some dykes have come up along lines of dislocation or true faults, the great majority occupy tension-cracks or fissures along which no displacement has occurred (Plates LIII., LV.).

Dykes vary in extent—some being considerably less than a mile in length, while others have been followed for distances of 50 or even 70 miles and more—often preserving throughout their course a wonderfully uniform thickness. Some of the smaller dykes do not seem to be more than a few inches in thickness; the longer ones, however, are much thicker, and sometimes reach, or even exceed, 100 feet in width. But although the shorter dykes usually tend to be thin, and the longer ones to be thick, there is really no definite proportion between the extent and the width of dykes in general. A dyke 20 feet thick may have a longer range than one double its width—or the converse may be the case. Although no general average can be given for the thickness of the more persistent dykes, yet it may be said that dykes measuring 20 to 40 feet across are among the commonest of those which have been followed for any considerable distance.

Occasionally, a dyke divides into two or more smaller ones, each pursuing the same general direction. Now and again, also, eruptive veins and veinlets proceed from a dyke, but this is apparently exceptional. Dykes often wedge out suddenly, both in lateral and vertical directions. Traced across country, they not infrequently seem to die out, and then after a shorter or longer interval they may as suddenly reappear. When a dyke of this kind is represented upon a map, therefore, we have the appearance of two or more dykes following each other along the same line. That the apparently separate dykes, however, are really portions of one and the same intrusion, has now and again been demonstrated in the coal-bearing districts—where a dyke has been followed continuously throughout all the coal-workings, although it fails in some places to reach the surface. Sometimes, indeed, a dyke cuts the lower coals but does not penetrate the higher seams in one and the same coal-pit. Very often a dyke is the product of more than one intrusion. As in the case of sills and other concordant intrusions (see p. 198) *multiple* and *composite* types may be distinguished.

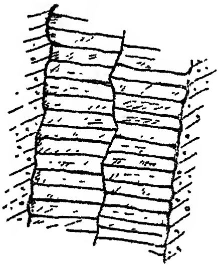


FIG. 80.—PRISMATIC JOINTING IN A DYKE.

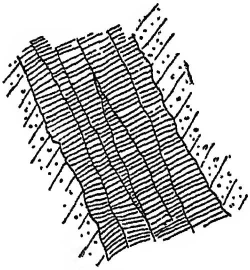
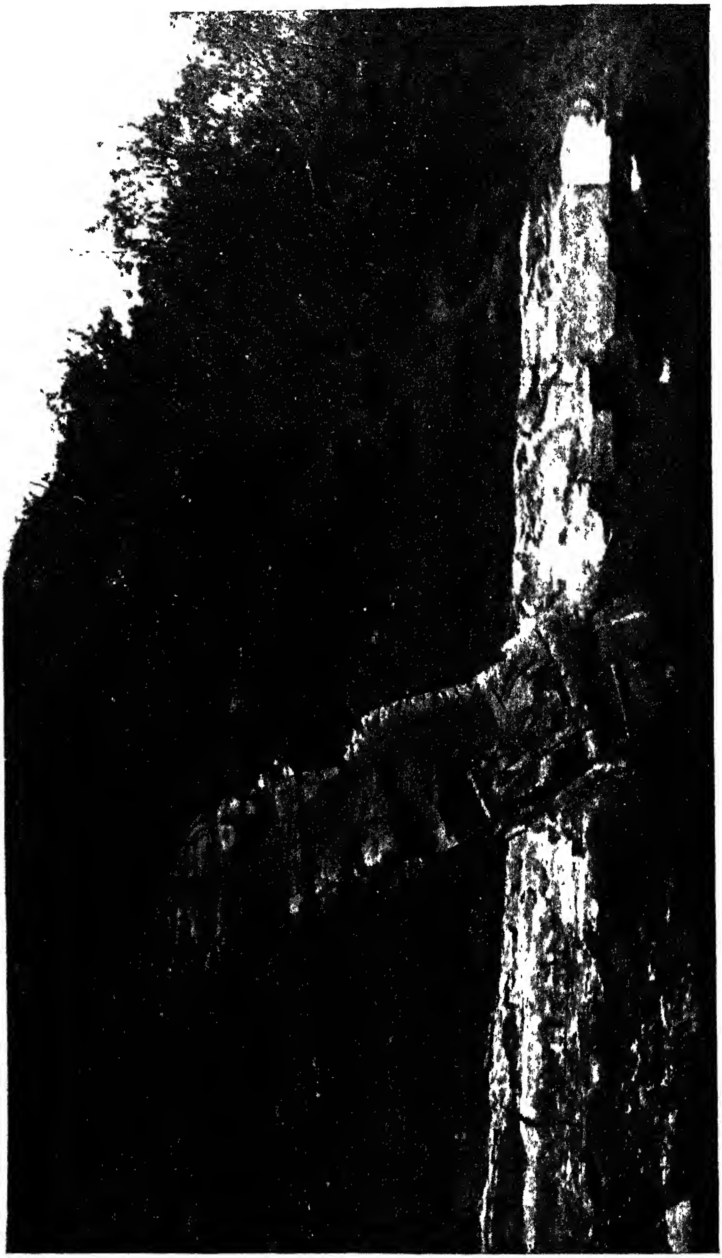


FIG. 81.—COMPLEX PRISMATIC JOINTING IN A DYKE.

Basalt-dykes are jointed most prominently at right angles to their direction—the jointing being frequently prismatic (see Figs. 80, 81). But, in some cases, the joints run parallel to the walls, so as to give the rock a kind of flaggy structure. Parallel jointing of this nature is usually, however, confined to the marginal areas of the rock.

The rock of a dyke is almost invariably finer grained along its margins than towards the centre—a structure which is most conspicuous in the case of the thicker dykes. Thin dykes are usually fine-grained throughout, yet even these tend to be most compact towards the sides. This structure is obviously due to the chilling effect of the contiguous rocks—the dyke along the line of junction becoming more or less markedly vitreous. Small vapour pores often appear at or near the margin, while larger pores, vacuoles, and occasionally irregular-shaped cavities of some size occur towards the centre,

PLATE LIII



BASALT DYKE CUTTING SANDSTONE AND SHALE, KILBRIDE BENNAN, ARRAN.

Photo by H.M. Geological Survey.

[*To face page* 203

either sporadically or forming a continuous medial zone running parallel to the direction of the dyke (Fig. 82).

Dykes affect the contiguous rocks much in the same way as sheets, but to a less extent. In the case of dykes only a few feet in thickness, the alteration produced is very slight, but the broader dykes may bake and indurate the rocks for a yard or two away.

Eruptive veins and dykes, as already indicated, often follow somewhat erratic courses. The more or less regular basalt-dykes of Western Scotland have been cited as good examples of wall-like intrusions. It need hardly be said, however, that injections of basalt, as of any other kind of igneous rock, are often extremely tortuous and branching (see Plate LIV.). The veins usually associated with granite, however, may be taken as somewhat characteristic of their kind. Of these two types are recognised —*exogenous* and *autogenous* or *endogenous* veins.

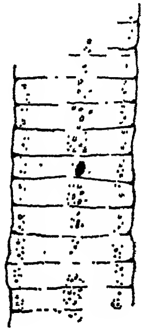


FIG. 82.—DYKE, SHOWING USUAL POSITION OF VAPOUR PORES AND VESICLES.

Exogenous Veins.—These are simply protrusions proceeding from a mass of granite into the contiguous rocks. They vary in thickness from mere lines or threads up to many feet or yards. Usually very tortuous, they ramify in all directions, intercrossing, dividing and subdividing again and again. Now and again, extremely thin veins have forced their way along planes of cleavage or of foliation. As a rule, however, small and large veins alike follow no definite direction—save that they stream outwards from the margin of the parent batholith—gradually diminishing in numbers as they proceed. In many cases the veins form a perfect network amongst

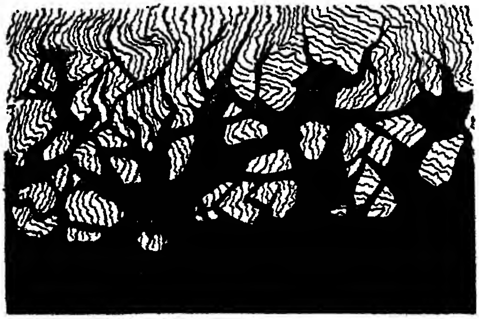


FIG. 83.—VEINS PROCEEDING FROM A MASS OF GRANITE.

which irregular fragments and larger masses of the invaded rocks appear as if entangled—forming what is termed an *injection plexus*. All the phenomena, indeed, seem to suggest that before the veins were injected the rocks surrounding a batholith had been so profoundly shattered, that molten matter found little difficulty in making its way amongst the fractured and sundered masses (Fig. 83).

The rock of these veins, especially the smaller ones, is usually finer grained than the granite-mass from which it comes. It is notable, also, that not infrequently it differs in petrographical character from that of the parent-rock—many of the veins consisting of quartz-porphyry or felsite.

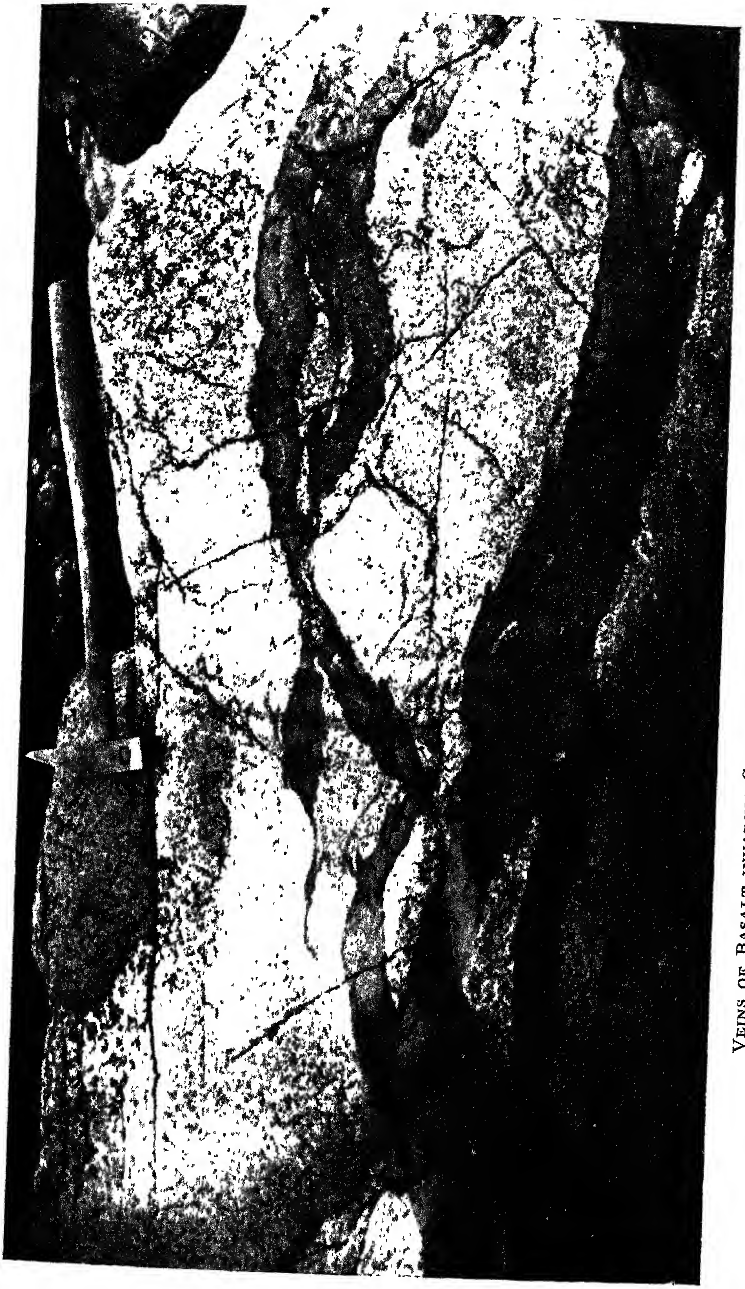
Endogenous or Autogenous Veins.—Some of these, *aplite-veins*, are composed of finer-grained rock than the granite; others, again, *pegmatite-veins*, are characterised by their greater coarseness and also by their irregularity of texture. Both types, although more acid, are related chemically and mineralogically to the granites which they cut; they represent, indeed, residual, volatile-rich mother liquors from the parent magma, which have been injected into rents formed in the surrounding solidified or partially solidified mass. Hence they are often spoken of as **contemporaneous veins.** The contemporaneous origin of both fine-grained and coarse-grained autogenous veins is shown by the fact that they are not always sharply separated from the parent-rock on either side. The mineral constituents of an autogenous vein often interosculate, as it were, with those of the surrounding granite, the crystals of the latter being so interlocked with those of the vein that the two rocks are not readily separated along the line of junction. Pegmatite-veins are frequently intruded into the country rock, and often extend for long distances away from the parent mass; aplite-veins, on the contrary, are for the most part restricted to the area of the granite itself.

Contemporaneous veins are met with in many other rocks, such as nepheline-syenites, syenites, diorites, gabbros, dolerites, teschenites, etc.

Ring Intrusions.—Around intrusive centres are found distinctive injected masses of two kinds, namely **Ring-dykes** and **Cone-sheets.** These intrusions have arcuate outcrops (see Figs. 84, 85), and, as Bailey and his co-workers have shown, the arcuate form is significant rather than accidental.

Ring-dykes.—The mode of intrusion of ring-dykes was first suggested by Clough, Maufe, and Bailey in their classic studies of Ben Nevis and Glen Coe—the term was introduced later in the Geological Survey Memoir dealing with the Tertiary and Post-Tertiary Geology of Mull. These workers found that at Glen Coe a cylinder, composed of Lower Old Red Sandstone lavas resting on Highland schists and bounded by a ring-fault, had subsided for thousands of feet within walls composed of the schists. The subsidence was accompanied on more than one occasion by the welling-up of magma along the fault fissure and its consolidation as

PLATE LIV



VEINS OF BASALT INVADING SANDSTONE, SHORE, NEAR KINGSCROSS POINT, ARRAN.

Photo by H.M. Geological Survey.

[*To face page* 204

ring-dykes of granite. In some cases of this type a surface caldera has been formed, and the magma of the ring-dykes reached the surface to be erupted as lava flows inside and around the caldera. In other cases a ring-fault has been interrupted by a cross-fracture, with the resulting formation of an underground cauldron of subsidence and the influx of magma into the cavity between the sinking block and its roof. According to Richey "repeated subsidences of the first-formed block, together with portions of the earlier intrusions, are believed to constitute the mechanism for the formation of a complete ring-dyke complex." As will be seen from Fig. 85, admirable examples of such complexes may be studied at Ardnamurchan. Ring-dykes are composed usually of coarse-grained rocks such as granites and gabbros, but medium-grained rocks such as dolerites and granophyres also occur and sometimes exceedingly fine-grained felsites. They are typically intrusions of large dimensions, ranging in width from a hundred yards to a mile or more. They are steeply inclined, and it has been demonstrated in some cases that the dip is away from the centre. Very often they are separated from one another by narrow strips of older rocks termed *screens*. One of the most striking ring-dykes known to science is that of Loch Ba in Mull. The late caldera of that centre is bounded by a complete ring-fault, along which extends

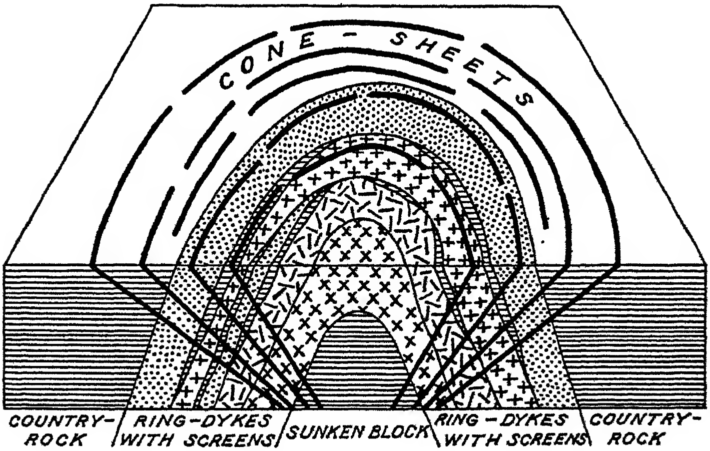


FIG. 84.—IDEAL RING-COMPLEX OF RING-DYKES AND CONE-SHEETS. (After J. E. Richey, *Trans. Geol. Soc. Glasgow*, vol. xix., 1931, p. 48.)

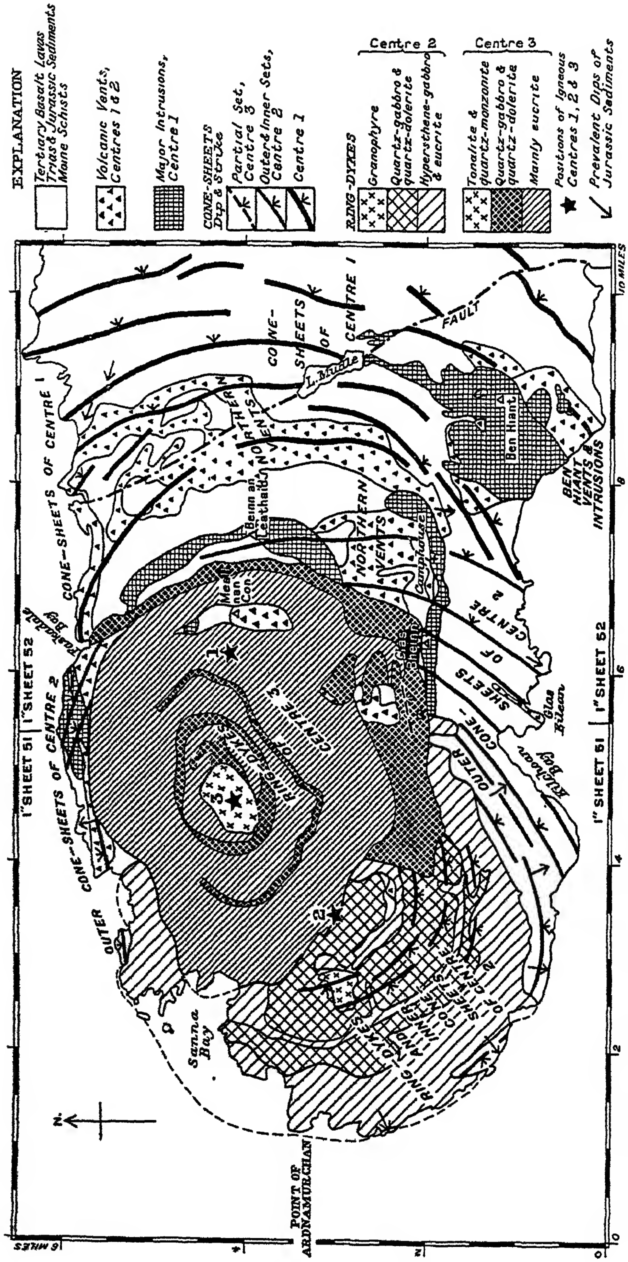

EXPLANATION
Tertiary Basalt Lavas Trias & Jurassic Sediments Moine Schists
Volcanic Vents, Centres 1 & 2
Major Intrusions, Centre 1
CONE-SHEETS Dip & Strike
Partial Set, Centre 3
Outer & Inner Sets, Centre 2
Centre 1
RING-DYKES
Centre 2
Granophyre
Quartz-gabbro & quartz-dolerite
Hypersthene-gabbro & eucrite
Centre 3
Tonalite & quartz-monzonite
Quartz-gabbro & quartz-dolerite
Mainly eucrite
Positions of Igneous Centres 1, 2 & 3
Prevalent Dips of Jurassic Sediments
CONE-SHEETS OF CENTRE 1
CONE-SHEETS OF CENTRE 1
NORTHERN VENTS
NORTHERN VENTS
L. Mudle
FAULT
Ben Hiant
BEN HIANT VENTS & INTRUSIONS
Beinn an Leathaidh
Meall nan Con
Camphouse
Glas Bheinn
Glas Eilean
Kilchoan Bay
Kilchoan
Fascadale Bay
CONE-SHEETS OF CENTRE 2
OUTER CONE-SHEETS OF CENTRE 2
RING-DYKES OF CENTRE 3
RING-DYKES AND INNER CONE-SHEETS OF CENTRE 2
OUTER
Sanna Bay
POINT OF ARDNAMURCHAN
1"SHEET 51
1"SHEET 52
N.
1
2
3
0
2
4
6
8
10 MILES
0
2
4
6 MILES

FIG. 85.—MAP OF RING-DYKES AND CONE-SHEETS, ARDNAMURCHAN. (After Plate II. in "The Geology of Ardnamurchan," *Mem. Geol. Survey*, 1930.)

almost continuously a ring-dyke of compact felsite. The maximum diameter of the ring is five miles.

Cone-sheets were first recognised by Harker in the Coolin Hills in Skye, when he mapped a group of centrally-inclined basic sheets to which he gave the name of *inclined sheets.* Since it was found that they occupy conical fissures they were renamed cone-sheets by the officers of the Geological Survey. As will be seen from Fig. 84, they are inclined inward and downward towards a common focal point, usually at an angle of about 45 degrees. Their outcrops form concentric belts around the same centres as the associated ring-dykes. There is always a central area devoid of cone-sheets. Cone-sheets are minor intrusions, consisting commonly of such rocks as dolerite, andesite, granophyre, and felsite. They are sometimes rather widely spaced, sometimes crowded together in very large numbers. From a study of the dynamics of ring-fractures, E. M. Anderson has concluded that both the ring-dyke and the cone-sheet fissures are due to strains set up in the roof of the magma-reservoir by varying pressure of the magma.

Excellent opportunities for the study of ring-intrusions are offered by the Scottish Tertiary intrusive complexes of Mull, Ardnamurchan, Skye, St Kilda, and Arran. Similar intrusions have been described also from Slieve Gullion, Carlingford, and the Mourne Mountains in Ireland.

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CHAPTER XIV

ERUPTIVE ROCKS: MODE OF THEIR OCCURRENCE—*continued*

Necks or Pipes of Eruption—their General Phenomena. Effusive Eruptive Rocks—Crystalline Effusive Rocks and Pyroclastic or Fragmental Effusive Rocks.

Necks are pipes or conduits of eruption—the throats, in short, of old volcanoes. They are filled either with crystalline rock or fragmental materials, or with both. They are of less deep-seated origin than batholiths; indeed, portions of the old volcanic cone are still to be seen surrounding a neck in some cases. As a rule, however, the cones have been entirely demolished—only the plugged-up vents remaining. Not a few of these seem to represent very small volcanoes—the products of single eruptions, like that which, in 1538, gave birth to the tuff and cinder cone of Monte Nuovo (Bay of Baiæ). Others, again, are obviously the relics of much more important volcanoes, from which were discharged not only fragmental materials but streams of lava. Between necks of this kind and certain bosses no hard-and-fast line can be drawn. Some of the latter may have had communication with the surface, and these, therefore, might equally well be described as necks. That term, however, ought rather to be reserved for the less important pipes or funnels of eruption—most of which, indeed, represent only the uppermost or terminal portions of such pipes. For, even in the case of the most highly denuded neck, we have no reason to suppose that the portion remaining occurred at any great depth below the base of the old volcanic cone to which it led. It is conceivable that, could we trace an important neck downwards, we should find it gradually assume the character of a more or less funnel-shaped boss, and this in its turn might, at a greater depth still, expand into a yet more extensive batholith. It would seem, therefore, as if the structure now presented by many an old focus of

Dyke of "White Trap" cutting through Black Carbonaceous Shale, near St Monans, Fife.

[*To face page* 208

eruption, may have been determined by the degree of denudation which it has experienced. With a minimum amount of erosion we have the cone of the extinct volcano, still recognisable as such. Increased erosion removes the cone, and then only a neck remains; until after some prolonged period the whole region becomes so reduced that the batholith or more deeply-seated portion is laid bare.

Seen in ground-plan, typical necks tend to be more or less circular or elliptical in form, but they are frequently irregular. Occasionally, however, such irregular shapes are suggestive of two or more closely adjacent necks having coalesced. Not infrequently, fissures, filled with agglomerate or tuff, pass outwards from a neck into the adjacent rocks. More remarkable than these, however, are certain vertical fissures of eruption which occur independently, or seem, at least, to have no connection with necks or pipes. At the surface, these appear in ground-plan as long, lenticular ribbons or belts, or they may expand and contract irregularly. They are filled with fragmental materials, and thus might be tersely described as *agglomerate-dykes*. Fissures of eruption of this kind are not common, and seem to be confined to regions where volcanic rocks are well developed. Isolated examples occur in Fife and in South Ayrshire, and they are met with likewise in the Cheviot Hills. Necks often appear upon a line of fault or dislocation, but in many cases no such connection can be traced. Although they now and again occur singly, they more usually cluster in groups within a limited area. They vary much in size, some measuring only a few yards across, while others may be several hundred yards in diameter; exceptionally, they may reach or even exceed a mile in width. They usually form more or less abrupt knolls or isolated hills, which vary in shape according to the nature of the materials of which they are composed. Many are more or less conical; others are somewhat steep and not infrequently craggy; while yet others are smooth and rounded. The rock occupying a neck may be crystalline, as basalt, andesite, phonolite, quartz-porphyry, felsite, etc. (see Fig. 86 and Plate LVII.); or it may consist of fragmental materials, as agglomerate or tuff (see Fig. 87), or both fragmental and massive crystalline igneous rocks may be present (see Fig. 88). Frequently the fragmental materials are extremely coarse—an aggregate of angular and subangular blocks and smaller stones in a matrix of finely comminuted débris, which may be meagre or relatively abundant. All the fragments may consist of crystalline igneous rock of one or more kinds, or these may be commingled with the débris of sedimentary rocks—the relative proportion of igneous and sedimentary materials varying indefinitely. Sometimes the contents of a neck consist of derivative rocks only, as sandstone, shale, limestone, ironstone, coal, etc. In necks composed mostly or exclusively of igneous materials, large broken crystals of various volcanic minerals sometimes occur, as hornblende, augite, biotite, sanidine, pyrope, etc. Still more remarkable is the appearance in some tuff-necks of abundant small and larger fragments of coniferous wood. Although the fragmental materials are usually somewhat coarse, yet not infrequently these are associated in the same neck with areas of much finer grained tuff; while in some cases the whole neck consists of fine tuff, which now and again has been so altered as to assume a crystalline or subcrystalline aspect.

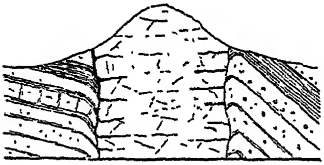

FIG. 86.—NECK OCCUPIED BY CRYSTALLINE IGNEOUS ROCK.

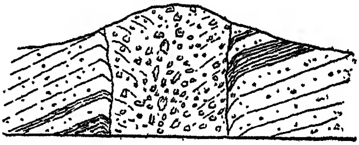

FIG. 87.—NECK OCCUPIED BY AGGLOMERATE.

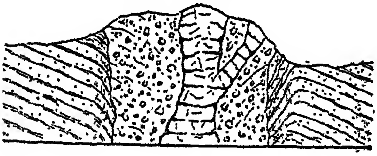

FIG. 88.—NECK OCCUPIED BY AGGLOMERATE AND CRYSTALLINE IGNEOUS ROCK.

The agglomerate and tuff often exhibit more or less distinct traces of a centroclinal dip—the materials being rudely bedded around the marginal area and inclined inwards towards the centre, where all trace of bedding is usually lost, although occasionally the coarse material appears roughly arranged in nearly vertical lines. Not infrequently it is about the centre of a neck that the larger blocks and stones are most abundant; but in many necks no such aggregation can be traced.

Massive dykes and branching veins of basalt or other crystalline igneous rock often pierce and ramify through the agglomerate and tuff. These may be confined to the neck itself, or pass outwards into the contiguous strata. The massive rock which often completely fills a neck is usually traversed by well-marked horizontal jointing, but in the case of large necks these joints are often confined to the marginal area, the rock towards the centre being, as a rule, very irregularly jointed.

The strata in immediate contact with a neck are often bent over suddenly, so as to dip abruptly against the old pipe of eruption—not infrequently, indeed, they are quite vertical, and sometimes much jumbled and broken, large blocks, slabs, and reefs having been detached or partially detached from the walls of the neck, so as to become enclosed wholly or partially in the tuff and agglomerate, while irregular veins of tuff pass outwards into the contiguous strata as if filling rents and fissures. Now and again, so great is the confusion that it is hard to follow the actual junction between the neck and the contiguous rocks. In such cases it seems as if the wall of the old funnel had collapsed and fallen in. The effect of heat upon the rocks abutting upon a neck is sometimes very notable—sandstones for a few yards away being converted into quartzite, and shales baked into a kind of porcellanite. On the other hand, not infrequently no alteration of any kind can be seen, coal having sometimes been mined close up against a neck without showing any trace of having been subjected to the action of heat. In other cases, coal has been rendered quite useless for many yards away from a neck, changed in fact into a soft, sooty substance. The amount of alteration produced bears no relation to the size of a neck; for while much change may occur round a small one, little or no alteration may be visible round one of much larger dimensions.

Explanation of Phenomena.—The necks described above obviously indicate the sites of former volcanoes. Many occur along lines of dislocation, just as is apparently the case with not a few volcanoes at the present time. On the other hand, a large number of necks seem to have no connection with any lines of weakness, and such pipes of eruption, therefore, must have been blown or blasted out by escaping vapours. Many necks probably indicate small puys—products of a single eruption, from which only loose ejecta were emitted. From others, one or more flows of lava have taken place. When the tuff and agglomerate of a neck consist wholly or largely of igneous materials, it is obvious that molten matter must have risen in the throat of the old puy, although it may never have flowed out as a lava. It is quite possible, however, or even probable, that lava-streams may have proceeded from many necks, around which no remains of such flows now exist. Subsequent denudation would well account for their disappearance, for not only have the volcanic cones been removed, but the surface upon which these were built up has also often been carried away. In the case of those necks which contain no igneous materials, but are filled exclusively with the débris of derivative rocks, it is clear that if at the time of eruption molten matter was present at all, it could only have been at a relatively great depth. The character of the débris, at all events, shows that only explosive vapours escaped by such pipes and funnels. While there is reason to believe that some necks may represent subaërial volcanoes, not a few are certainly of subaqueous origin. In the former case no trace of the old cones or the surface upon which they were accumulated has been preserved—the pipes alone remain to tell their tale. From the fact, however, that these sometimes contain quantities of coniferous wood, which from its appearance must have been buried in a fresh state, it has been inferred that some volcanoes were probably subaërial, and that after their extinction they became clothed with a coniferous vegetation. The majority of the necks met with in Scotland, however, would seem to represent subaqueous volcanoes. This is suggested by the simple fact that the cones are occasionally preserved—which could hardly have happened had the volcanoes erupted upon a land-surface. The volcanoes referred to obviously discharged their ejecta upon the gradually subsiding bed of sea, lagoon, or lake, and thus the sheets of materials that accumulated round the vents passed outwards in all directions and became interstratified with sediments, charged with the organic remains of the period. When at last the volcanoes became extinct, they were finally covered up by successive deposits of sediment, and thus the cones escaped the denudation that ere long must have demolished them had they been formed upon dry land (see Fig. 89).

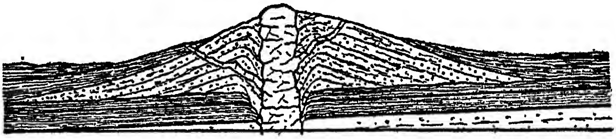

Fig. 89.—Cone of Agglomerate, and Neck of Crystalline Igneous Rock.

The inward dip of the strata surrounding a neck has been attributed to that sinking of surface which so frequently takes place near a volcanic centre. After prolonged activity the rocks surrounding a vent probably become undermined, and this must tend to bring about subsidence in its immediate neighbourhood. In the case of extensive necks, from which much material has been discharged, the inward dip of the surrounding strata may be due to some such cause. A large number of the necks, however, are too small and erupted for too short a period to have produced any marked subsidence of the surrounding rock-masses—and yet the abrupt inward dip of the strata surrounding such necks is quite as conspicuous as in the case of larger ones. It would seem more likely that the sudden inward dip of the rocks abutting upon a neck is due partly to the downward drag of the fragmental materials while they were slowly subsiding and becoming consolidated, and partly, perhaps, to the unequal yielding of the strata themselves before the pipes were filled. When a subaërial puy became extinct, the loose materials forming the cone would naturally tend to slip down into the crater and funnel, while at the same time the walls of the vent, exposed to the action of springs and to weathering generally, would also supply material—all this débris falling into the vent would form a steep, rudely-bedded talus having a centroclinal dip. The falling away of the softer and less resistant rocks in the walls of the vent would tend to undermine the less yielding beds above them, and thus cause these to bend over. Finally, when the pipe had become filled, the consolidating débris, as it subsided, would drag down the rocks forming the walls, and thus increase their inward dip. In the case of a submarine puy there would be no weathering action upon the walls of the pipe, but it seems at least unlikely that the rocks should remain unaffected, and that larger and smaller portions should not become detached, and thus cause undermining and bending downwards of the rocks above. It is worthy of note, however, that this inward dip of the strata abutting against a neck does not invariably occur.

Necks, like batholiths, may belong to almost any geological period. But inasmuch as a typical neck represents the upper portion of a pipe of eruption, and consequently is not of deep-seated origin, only those of subaqueous eruptions can date back to the earlier geological ages. Now and again, it is true, some Palæozoic necks seem to have erupted on land, but, if so, they must ere long have been submerged, for only in this way could these have escaped demolition. Exposed for a prolonged period to denudation, not only must the cones have been demolished, but the ancient land-surface on which these stood must have been so lowered that the upper portions of the pipes of eruption—the necks—would have been planed away, and the deeper-seated roots of the old volcanoes laid bare.

EFFUSIVE ERUPTIVE ROCKS

Effusive rocks have been erupted at the earth's surface, and are of two types, *crystalline* and *fragmental*—that is to say, *lavas* and *tuffs*. As they frequently occur interstratified in a conformable manner with derivative rocks of all kinds, they are often termed *contemporaneous* or *interbedded.*

(*a*) **Crystalline Effusive Rocks.**—The general petrographical characters of these rocks have been already set forth. It will be remembered that lavas are often scoriaceous above and below, and in some cases may be more or less porous and cavernous throughout. The vapour-cavities are often flattened or drawn-out in the direction of flow. In all such lava-form rocks residual glassy matter is very commonly present, especially towards the upper and under surfaces.

The mineral constituents also frequently show glass- and stone-inclusions, while liquid-cavities are relatively seldom seen. Now and again the lower part of a lava is crowded with indurated arenaceous and argillaceous matter, and contains occasionally well water-worn stones, as if the molten matter had flowed over the bed of the sea or of a lake or river, and thus caught up and enclosed some of the sedimentary materials lying in its path. Even fragments of trees have been found included in the basal portion of a lava—as in the case of a Carboniferous basalt-flow near Kinghorn, Fife. In all these respects effusive crystalline rocks differ markedly from intrusive rocks. As further differentiating lava-form rocks from sills, with which they might sometimes be confounded, it may be noted that while the former may produce some induration of the rocks on which they rest, they never affect the overlying strata. Obviously, the superjacent beds have been deposited over the surface of the lava-form rock after consolidation had taken place, for the lines of bedding follow all the irregularities of the underlying rock-surface. When this is much rent and cleft, the cavities have been gradually filled up with sediment, while now and again fragments of the scoriaceous crust of the old lava have been detached and enclosed in the immediately superjacent aqueous rock. Again, it may be noted that lava-form rocks are usually associated with stratified tuffs (see Fig. 90).

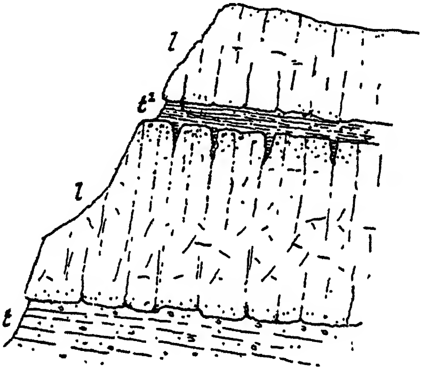

FIG. 90.—EFFUSIVE IGNEOUS ROCKS.

l, *l*, lava-flows; *t*, tuffaceous sandstones; t^1, tuffaceous shales.

Flows vary in thickness, some being only a few feet, while others attain a depth of many yards. The more basic

PLATE LVI

TERTIARY LAVAS (BASALTS). BEINN EDRA, TROTTERNISH, SKYE.

Photo by Robert M. Adam.

[*To face page* 215

lavas generally preserve a somewhat equable thickness, the intermediate and acid kinds tending rather to be irregular, so that they thicken and thin-out more or less rapidly.

(*b*) **Pyroclastic** or **Fragmental Effusive Rocks.**—The tuffs usually associated with lava-form rocks vary in character. As might have been expected, their dominant ingredients consist of the comminuted débris and larger fragments of the lavas they accompany. Thus we have basalt-tuff, andesite-tuff, trachyte-tuff, etc. All varieties of texture and structure are met with, some rocks being very fine grained, while others are mere aggregates of lapilli and blocks—finer and coarser grained materials often rapidly alternating in a vertical section. Bedding is usually pronounced—many of the finer tuffs being beautifully laminated. Occasionally, very large sporadic blocks and bombs may be encountered in a bedded mass of small lapilli, and generally increase in numbers as the old focus of eruption is approached. Tuffs are frequently interstratified with ordinary sedimentary beds, and when such is the case the tuffs themselves usually contain a larger or smaller proportion of arenaceous or argillaceous materials, and thus frequently graduate into sandstone and shale. Fossils may be included not only in the sedimentary beds associated with tuffs, but in the tuffs themselves. Fragments of plants, and various marine organic remains, for example, not infrequently occur in the tuffs and tuffaceous sandstones and shales, which are associated with the lavas of the Carboniferous system in Scotland.

Mode of Occurrence of Effusive Rocks.—Sometimes a flow, with its accompanying tuff, occurs singly; more usually, however, flows and tuffs appear in consecutive series. Some effusive rocks, occupying a limited area, are obviously the products of an isolated volcano. Others extend over very wide regions, and appear to represent the products of a series of more or less closely associated foci of eruption, the successive lavas and tuffs discharged from the several vents interosculating and overlapping. A good example is furnished by the eruptive rocks of the Sidlaw and Ochil Hills, some of the old vents from which these were discharged being still recognisable in the great necks and bosses which have been exposed by denudation. In other cases of widely extended effusive rocks, we appear to have the products of vast fissure-eruptions. Of such a character are the great lava-fields of the Columbia and Snake

Rivers in the United States of America, and the Deccan "traps" of India. A similar origin was advocated by Sir A. Geikie for the Tertiary basalt lavas of Western Scotland and Antrim (Plate LVI.). Recent researches in Mull, however, have shown that, like the basalts of Iceland, the British Tertiary plateau-basalts may be, in part at least, the products of "shield volcanoes" of the Kilauean type.

Sandstone Dykes.—Here brief reference may be made to certain abnormal dykes, composed of sedimentary materials, and occupying vertical fissures, which have been filled sometimes from above, sometimes from below. Some of these dykes have a length of several miles, and their precise mode of origin is obscure. The sand may have been introduced during earthquake movements, and such dykes, indeed, have been spoken of as "natural seismographs.".

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CHAPTER XV

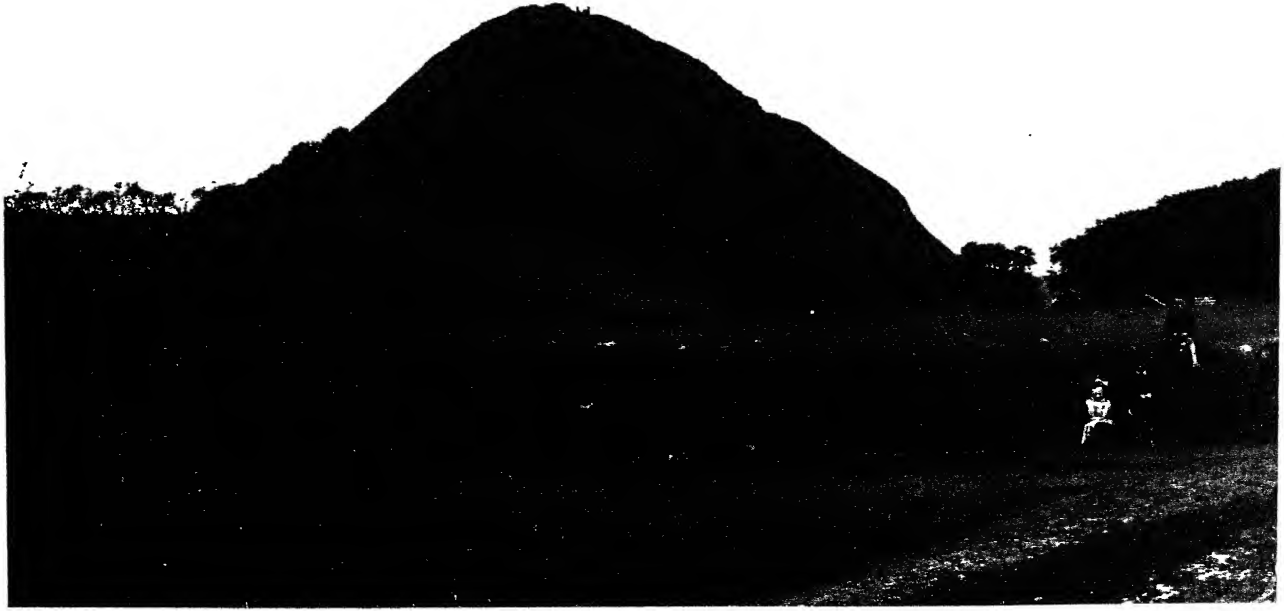
ALTERATION AND METAMORPHISM

Rock-changes induced by Epigene Action. Deep-seated Alteration or Metamorphism. Degrees of Metamorphism. Thermal or Contact Metamorphism. Dynamic Metamorphism. Dynamothermal Metamorphism. Plutonic Metamorphism.

Alteration by Epigene Action.—Very few rocks have not undergone some change since the time of their formation. At and for some distance down from the surface, water passes more or less readily along the various planes of division by which all rocks are traversed—not only so, but it soaks into the rocks themselves, occupying their minutest pores and capillaries. In this way chemical changes of greater or less importance are effected, by which certain rocks tend to become disintegrated, while others, on the contrary, are more firmly consolidated. Crystalline igneous rocks, as a rule, are prone to decay—their feldspathic and ferromagnesian constituents being readily broken up chemically, and some portion of their substance removed in solution. Many schistose rocks experience the same kind of change—a change which usually results in weakening a rock—its hardness and solidity becoming more or less impaired. Sedimentary rocks, on the other hand, being themselves the products of decay and disintegration, and consisting therefore of more stable ingredients, are less liable to those chemical changes to which igneous and schistose rocks alike are subject. Instead of being weakened by the action of percolating water, they are often strengthened by the introduction into their pores and capillaries of various mineral substances which bind their ingredients more firmly together. To this general rule there are, as might have been expected, many exceptions. Percolating water, which introduces cementing materials, may in the course of time redissolve these and carry them away. Again, rocks of chemical origin, such as travertine, dolomite, etc., and rocks organically derived, such as chalk and many limestones, being all more or less soluble, are readily attacked by percolating water. To sum up in a few words, it may be said that the chief chemical changes induced in rocks by the process of weathering, consist of hydration, oxidation, and carbonation, with the consequent formation of oxides and hydrated oxides such as hæmatite and limonite, hydrated silicates such as kaolin and chlorites, and carbonates such as calcite and dolomite.

Metamorphism.—The changes brought about by epigene action, however extreme they may be, must not be confounded with true metamorphism. The term "metamorphic" is applied properly to rocks, the textural and structural characters and mineralogical constitution of which have been more or less profoundly affected in response to changes of temperature, stress, and chemical environment. Metamorphism, however, varies much in its intensity. It may be so inconsiderable as not to obscure many of the original characters, or so extreme that we can only conjecture what the nature of the original rock may have been. True metamorphism, especially that which has resulted in crystallisation or recrystallisation and the production of schistosity, foliation, and granoblastic structures, would seem to have taken place at greater depths than those at which weathering and cementation occur. The great majority of metamorphic rocks are crystalline and either granoblastic, schistose, or foliated, and it is only rarely that they are likely to be mistaken for igneous or derivative rocks altered by weathering or hydrothermal action. Nevertheless there are certain altered rocks which in hand specimens might well pass for products of metamorphism. Sands and sandstones, for example, have frequently been transformed into "quartzite" by percolating water carrying silica in solution; and hand specimens of such rocks might readily be taken for quartzites of truly metamorphic origin. "Serpentine" affords another example of a rock which has resulted, sometimes from alteration, sometimes from metamorphism. Metamorphic serpentine, however, is usually foliated, and, moreover, is always associated with other crystalline schistose rocks. On the other hand, serpentine which has been produced by the hydrothermal alteration of ultrabasic igneous rocks is not usually foliated and is found traversing rocks of all kinds. Cases like these, however, are exceptional, and there is usually no difficulty in distinguishing

PLATE LVII



NORTH BERWICK LAW, HADDINGTONSHIRE. [Neck of a Carboniferous Volcano plugged up with Trachyte.]

Photo by H.M. Geological Survey.

[*To face page* 218

in the field between metamorphic rocks and rocks which are products of weathering or hydrothermal alteration.

There are many degrees of metamorphism. In some cases rocks have been so slightly changed that many of their distinctive characters have remained unaffected. In the transformation, for example, of a siliceous sandstone into a metamorphic quartzite the only conspicuous change is one of texture; while becoming completely recrystallised, so that the difference between quartz grains and siliceous cement is entirely obliterated, the rock has yet retained its original chemical composition and major structures. Thus planes of stratification, false-bedding, ripple-marks, etc., may be as conspicuous in a quartzite as in any unaltered sandstone. Usually, however, a rock, while it may show little or no change in its chemical composition, nevertheless has been profoundly modified as regards its mineral constitution and structure. An argillaceous shale, for example, may be transformed into an andalusite-mica-schist or andalusite-hornfels. But although the chemical composition of rocks has often been little affected by metamorphism yet this is not invariably the case. Sometimes there has been a loss of certain chemical constituents, volatiles such as carbon-dioxide, water, etc., having been driven out; sometimes, on the other hand, new materials—silica, alkalies, fluorine, etc.—have been introduced.

Several kinds of metamorphism have been recognised: (a) *thermal* or *contact metamorphism*, which results from rise of temperature without any marked intervention of the stress factor; (b) *dynamic metamorphism*, brought about mainly by stress without any important accompanying rise of temperature; (c) *dynamothermal metamorphism*, in which both the thermal and the stress factors are of prime importance; and (*d*) *plutonic metamorphism*, in which depth, very high temperatures, and uniform pressure are all important. The terms *local* and *regional* or *general* have also been used. The former connotes metamorphism localised either around intrusive igneous masses or along narrow belts where changes have been superinduced by dynamic or thermodynamic factors; the latter implies metamorphism which is not localised but has affected extensive tracts of the earth's crust.

(*a*) **Thermal or Contact Metamorphism.**—Incipient metamorphism of this type is seen at the lower contacts of lava-flows, the adjacent rocks showing such changes as induration, change of colour, and the production of prismatic jointing. The changes caused by intrusive eruptive rocks, however, are usually more pronounced. Sometimes, indeed, they are of slight importance and confined to the immediate proximity of the intrusion; but at other times they have resulted in the formation of an aureole of metamorphic rocks (see Fig. 91) which may extend outwards from the margin of the eruptive mass for a distance of several miles. The extent and intensity of the metamorphism depend on a number of factors. Other things being equal, the width of the aureole will be determined mainly by the size of the intrusion, but it will be, influenced also by the form of the intrusive body, becoming narrower where the junction is steeply inclined and wider where it becomes more nearly horizontal. The initial temperature of the intrusion, which is different for different kinds of magma, the rate of cooling and the proportion of water and other volatiles present will all obviously affect both the extent and the intensity of the metamorphism. The vitrification of shales and sandstones at the margins of very small basaltic intrusions reflects, for example, the high initial temperature of basic magmas. The more pronounced metamorphic effects produced by granites as compared with other plutonic rocks are due to the fact that granite magmas are exceptionally rich in chemically-active gases and liquids. But the extent and intensity of this type of metamorphism depend also on the

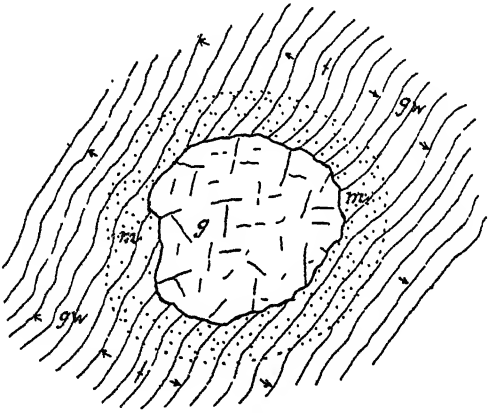


FIG. 91.—PLAN OF A BATHOLITH WITH AUREOLE OF METAMORPHOSED ROCKS.

g, granite; *gw*, greywackés and shales; *m*, metamorphosed rocks.

varying composition and textural characters and on the initial temperature of the rocks which are undergoing the metamorphism. Some rocks react more readily to temperature changes than others, and an open-textured rock will offer easier access to gases and solutions than one which is close-grained and compact.

Within an aureole of metamorphosed rocks round a batholith it is possible to recognise zones of progressive metamorphism. When the original rocks are of one more or less uniform type this is a relatively simple matter. A classic illustration is Rosenbusch's description of the contact metamorphism of the Steiger slates round the granite mass of Barr-Andlau in the Vosges. There an outer zone of *Knotenschiefer* or spotted slates is followed by a middle zone of *Knotenglimmerschiefer* or spotted mica-schists, and this in turn by the innermost zone of *Andalusite-hornfels*. In the outer zone the spots are aggregations of graphitic matter representing carbonaceous material originally disseminated throughout the slate. Apart from the development of the spots the rocks in this zone have undergone but little change. The spots in the middle zone are incipient crystals of andalusite, and here there has been an abundant development of micas and quartz, the former having grown along the cleavage planes in such a way as to obliterate that structure and give the rock a schistose character. In the innermost zone there has been complete reconstruction of the rock into a fine-grained granoblastic aggregate of crystals of andalusite, cordierite, biotite, muscovite, magnetite, and quartz. In recent years more precision has been attained in marking off successive zones by noting the first appearance of distinctive new minerals, the formation of which implies the reaching of certain minimum temperatures. When the original rocks of the aureole have consisted of alternations of different rocks attention may be focussed on the progressive metamorphism of one or more particular types of rock.

Induration and the development of " spots " and " knots " are features characteristic of the outer limits of metamorphic aureoles. The spots in argillaceous rocks may be graphitic aggregates, or they may consist of indeterminable amorphous material, or they may be recognisable as incipient crystals of andalusite or cordierite. As the intrusion is approached increasing metamorphism is marked by the coming in of successive new minerals and by an increasing amount of crystallisation or recrystallisation, finely-schistose structures giving place to granoblastic and often, in the highest grades, to thoroughly gneissic structures. Thus from shales and slates may be formed with medium-grade metamorphism such rocks as andalusite-mica-schist, andalusite-hornfels, and cordierite-biotite-hornfels, while common types found in the highest grades are hypersthene-orthoclase-cordierite-hornfels and sillimanite-gneiss, or, from rocks originally poor in silica, hornfelses rich in spinels or corundum. The purer arenaceous rocks give rise to quartzites. From impure sandstones of the greywacké type may be derived gneisses with abundant cordierite, garnet, or sillimanite. A pure limestone crystallises to give a marble, from which usually all traces of organic structures have disappeared. Many limestones, however, contain siliceous, aluminous, and ferruginous impurities, and the presence of these gives rise to the development of lime-rich silicates such as lime-garnet, wollastonite, vesuvianite, diopside, tremolite, sphene, zoisite, and epidote, or, at high temperatures, anorthite. Dolomites, as we have seen (p. 89), undergo a process of dedolomitisation, in which the dolomite is reduced to calcite and the magnesia, either alone or in combination with impurities, forms new minerals. Calcareous shales or very impure limestones are reconstructed to give rocks made up entirely of lime-rich silicates and known as calc-silicate-hornfelses. When igneous rocks are affected by intrusions they also may be partially or completely reconstructed. Basic types are more susceptible to temperature changes than acid types, and weathered rocks than those which are unaltered. A good illustration of complete reconstruction is seen in the transformation of basalts and dolerites into garnet-hypersthene-labradorite-granulites (see Plate XXV. 3). Schists also may be more or less completely reconstructed by contact metamorphism, a conspicuous feature being the development of granoblastic structures leading to the partial or complete effacement of the schistosity.

Not only are rocks of all kinds more or less metamorphosed by intrusive masses, but the igneous masses themselves are not infrequently affected by the rocks among which they have been intruded. Remarkable examples have been cited by Lacroix from the granite massif of Quérigat in the Pyrenees. There, by partial solution of limestones, the granite locally loses its quartz and becomes converted into a hornblende-mica-diorite, or, where solution has been more advanced, into norite and hornblende-peridotite. Of great interest, too, in this connection are the studies by Read of the contaminated gabbros of Aberdeenshire, where, by incorporation of argillaceous xenoliths, the gabbros have been transformed into norites containing minerals such as cordierite, spinel and garnet which are not normally present in igneous rocks.

It is believed that water has played an important rôle in thermal metamorphism. Deep-seated magmas probably contain large supplies of water and other vapours and gases dissolved in them, the presence of which must increase the liquidity of the molten masses. Indeed, direct evidence of the existence of this contained water is supplied by volcanic phenomena, vast volumes of steam and vapours issuing from craters and escaping from lavas. Unaltered sedimentary rocks also contain considerable stores of water, for all are more or less porous, and are thus capable of retaining a larger or smaller proportion of interstitial moisture. In addition to this supply we must take note of the fact that many of the mineral constituents of rocks contain water in chemical combination. It is not surprising, therefore, that the more important metamorphic changes effected by a batholith are just such as should have been produced by steam permeating the rocks under great pressure and at a very high temperature. The steam has simply acted as a solvent menstruum, and has tended to produce a more or less perfect crystallisation or recrystallisation of the constituents of the rocks affected, leaving the chemical composition practically unchanged.

It is only generally true, however, that metamorphism has left the chemical composition of rocks unchanged. Not infrequently, silica has been introduced in abundance from batholiths, so as to permeate the contiguous rocks and to fill up cracks and fissures. The rocks of the metamorphic zone are thus frequently more or less abundantly traversed by smaller and larger veins of quartz, which in places may extend outwards almost to the very margin of the zone, but they rarely go beyond it. In some cases, these quartz-veins are accompanied by new minerals, the composition of which shows that they could not have been derived from the alteration of the surrounding rocks. Among the most interesting examples are the tin-bearing veins associated with intrusive masses of granite and other acid eruptives, and the apatite-veins which are more particularly connected with batholiths of gabbro. In the formation of the cassiterite-veins, various volatile fluorides, boron-compounds, etc., have taken part; for the tin-ore is usually accompanied by fluor-spar, schorl, etc. According to Professor Vogt, the contents of such veins were extracted from the granite before the plutonic mass had fully congealed. This is proved by the fact that the same series of elements which characterise the cassiterite-veins occur also in the pegmatite-veins of granite. In the case of the apatite-veins, analogous phenomena appear, the elements they contain being the same as those met with in gabbro. Thus, while potassium and lithium minerals are characteristic of tin-veins, magnesium and calcium-sodium minerals are notable constituents of apatite-veins. "In both classes of veins," Vogt remarks, "we find a characteristic pneumatolytic metamorphism of the country-rock. Each class has in abundance a halogen element, the tin-veins carrying fluorine (with a very little chlorine), and the apatite-veins chlorine (with a very little fluorine)." He concludes, therefore, that the materials of the apatite-veins have been extracted from the gabbro magma, just in the same way as the contents of the tin-veins have been obtained from granite. In the former case, an aqueous hydrochloric solution has been concerned in the extraction process, while in the latter case this process has been based chiefly upon a reaction in the presence of water of hydrofluoric acid dissolved in the granite magma.

Not improbably, many other veins, rich in ores of various kinds, which occur in close association with eruptive rocks, have originated in the same way as the tin-veins and apatite-veins. The veins referred to are usually independent of the character of the rocks they traverse, while a more or less clear genetic connection can be established between them and the eruptive masses. Moreover, the rocks in which they occur are always metamorphosed in a less or greater degree; they have obviously been permeated by mineralising agents, or subjected to a kind of solfataric action. (See further under "ORE-FORMATIONS.")

The following conclusions appear to be well established as a result of the study of Thermal or Contact Metamorphism :—

1. Rocks of all kinds are liable to become metamorphosed at their contact with eruptives—the nature of the changes depending partly on the chemical composition of the invaded rocks and partly on the petrographical character and the volume of the intrusive masses.

2. Metamorphism has usually been effected without any marked alteration of the chemical composition of the rocks attacked.

3. In certain cases, however, highly heated solutions, derived from plutonic intrusions, have penetrated and permeated contiguous and surrounding rocks, and thus, by introducing new materials, have altered more or less considerably their chemical composition.

4. Crystallisation has been superinduced by metamorphism in derivative rocks, while igneous and schistose rocks have in like manner been recrystallised.

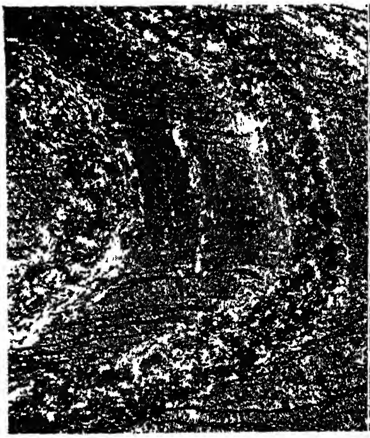
5. The production of new minerals is a common accompaniment of thermal metamorphism.

6. Now and again rocks near their contact with a batholith may be rendered gneissose (Plate VI. 2); sometimes schistosity has resulted from the development of minerals such as micas and amphiboles along pre-existing planes of bedding or cleavage; more usually the rocks produced by contact metamorphism are granoblastic in structure.

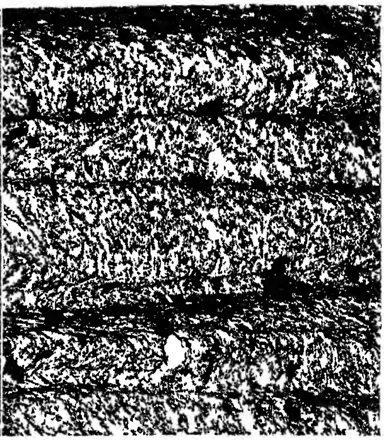
7. The petrographical character of a batholith is sometimes considerably modified by that of the rocks it has invaded. Apparently this is due to the latter having been to some extent absorbed and assimilated by the intrusive mass.

(*b*) **Dynamic Metamorphism.**—Here we may include all the metamorphic changes superinduced on rocks by strong mechanical forces at low temperatures—what Harker has termed *pure dynamic metamorphism*. At great depths in the earth's crust, and in the central portions of belts affected by orogenic movements, where pressure and temperature conditions are both high, all rock deformation is brought about by plastic flow and recrystallisation. It is otherwise, however, along restricted belts of compression at more shallow depths and in the marginal parts of regions of orogenic disturbance. There rocks and minerals differ greatly in the resistance they offer to deformation and in their behaviour when that resistance has been overcome. In hard and brittle rocks, such as granites and arenaceous sediments, cataclastic phenomena (fracturing, crushing, etc.) are conspicuous; in the softer, less brittle and more yielding rocks, such as argillaceous sediments and tuffs, the development of slaty-cleavage is the most noteworthy feature of the metamorphism. Not infrequently, however, as we shall see, the cataclastic

PLATE LVIII



1.



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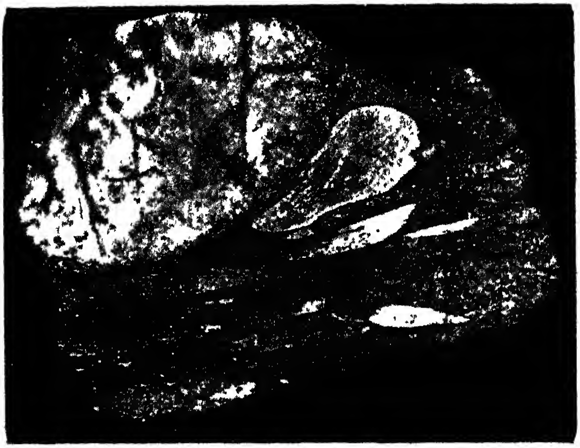

3.

1. Phyllite with coarse calcareous bands, Kilchiaran, Islay. Shows folding and strain-slip cleavage. × 5.

2. Part of the fine-grained phyllite of No. 1, showing relation of the strain-slip cleavage to the puckered folding. × 50. (See p. 226.)

3. Schistose Conglomerate. Nearly natural size. (From Lehmann's *Entstehung der altkrystallinischen Schiefergesteine.*)

[*To face page* 225

effects and the cleavage are accompanied by a certain amount of solution and recrystallisation.

Slaty-Cleavage.—In a preceding chapter (p. 127) the phenomena of rock-folding were discussed, and it was there pointed out that the constituent ingredients of a folded rock were often more or less deformed or distorted. Deformation of the kind referred to is often conspicuously developed in areas of regional metamorphism, more especially along their outer margin. In this peripheral zone the rocks may be arranged in more or less steeply inclined positions, but they are neither crystalline nor foliated. Nevertheless, they usually show evidence of having been compressed. This is shown by the superinduced structure known as *Slaty-Cleavage*, a structure which renders a rock capable of being cleaved or split into slabs, plates, or laminæ in a direction independent of the planes of bedding. It has been shown that in certain cleaved rocks this is in part due to the flattening of original clastic constituents in one and the same direction; in others it can be demonstrated that some of the original clastic minerals of flaky habit have been rotated into approximate parallelism along planes of compression. Modern microscopic studies of thin slices of fine-grained clay-slates have shown clearly, however, that the parallelism of the dominating flaky constituents is due to the fact that they have, to a large extent, developed in place, orientating themselves as they grew in planes perpendicular to the maximum pressure. These flaky minerals are chiefly micas, chlorites, and iron oxides. In the case of a shale the rock can be split readily along planes of deposition; in the case of a clay-slate the direction of easy fissility is that of the cleavage planes, which are planes due directly or indirectly to compression. That slaty-cleavage is one of the concomitant results of crustal deformation is shown by the planes of cleavage being always parallel to the axial planes of anticlinal and synclinal folds (see Fig. 129). When the structure is well developed, not only does the original lamination disappear, but even the planes of bedding may be rendered obscure or altogether obliterated. The direction of bedding is not infrequently indicated, however, either by colour differences or by the presence of bands of varying texture. Cleavage may intersect the bedding planes at any angle, or it may now and again coincide with these when the limb of a fold is inclined in the same direction and at the same angle as the planes of compression. Slaty-cleavage is best developed in fine-grained homogeneous clay-rocks, which are sometimes so fissile that they can be divided with ease into very thin, smooth plates. It is not confined, however, to argillaceous strata, but may affect rocks of the most diverse character, as greywacké, tuffs, and crystalline eruptive rocks; but in such rocks it is never so well developed, the planes of cleavage being usually imperfect and more or less irregular and discontinuous. Despite the generation or regeneration in place of much of the flaky material in clay-slates, the original clastic character of the rocks is usually obvious when they are studied in thin slices. With increasing metamorphism they pass into phyllites, in many of which all original clastic material has disappeared and the new minerals developed indicate the intervention of considerable elevation of temperature. Such rocks are transitional between clay-slates and mica-schists which are the most characteristic products of the dynamothermal metamorphism of argillaceous rocks.

Another structure which not infrequently arises in argillaceous rocks as a result of dynamic metamorphism is *strain-slip cleavage*. Unlike slaty-cleavage this is not a property of *any* plane parallel to a given direction in the rock. The fissility resulting from strain-slip cleavage takes place along parallel planes at certain small distances apart. The rock has yielded to pressure by the formation of close-packed, minute, inclined or asymmetrical folds, which have yielded along their middle limbs to give minute faults, the position and direction of which determine the splitting planes. Strain-slip cleavage of this type is illustrated in the photomicrographs of a phyllite shown in Plate LVIII. 1 and 2. In Fig. 1, which shows "major" folding as well as the minute puckering and strain-slip cleavage, the latter structure is well developed in the phyllitic layers but is absent in the associated crystalline calcareous bands.

The dynamic metamorphism of harder and more brittle rocks leads to fracturing, crushing, and deformation with the production of cataclastic structures. In the absence of pronounced lateral shearing coarse breccias may be formed, made up of angular rock fragments. When rotational movement of the fragments has taken place, with consequent rounding, the resulting product is a crush-conglomerate. The crush-conglomerates of the Isle of Man, described by Lamplugh, were formed by the fragmentation of bands of grit intercalated in shales. The grit fragments became rounded by attrition, while the shale, which yielded by flowing, was forced between the " boulders " of grit and developed slaty-cleavage. Where the fragmentation is accompanied by large-scale dislocation, as, for example, in regions of overthrust movements, lenticular and parallel structures become conspicuous. At some distance from the movement planes lenticular cores (or *phacoids*, as they are termed) of the original rocks can still be observed, around which finely-pulverised and recrystallised materials are arranged in much the same way as the smaller ingredients of a lava have grouped themselves about a phenocryst. As the thrust-planes are approached, the phacoidal masses become smaller. Ultimately even the small " augen " of individual, resistant minerals disappear and the rocks become *mylonites*, a term applied by Lapworth to rocks which have been completely pulverised and rolled out or " milled " by differential movement. Irrespective of the characters of the original rocks the final result is usually the production of exceedingly compact, close-textured rocks showing banded structures which recall the flow-structures of rhyolites. When movement has been unusually intense and rapid, so much frictional heat has been generated that actual fusion has sometimes resulted, and the black, amorphous rocks so produced are known as *flinty-crush rocks* or *pseudo-tachylytes*.

(*c*) **Dynamothermal Metamorphism.**—This type of metamorphism, which is brought about by the working together of directed pressure and heat, is characteristic of many extensive areas of crystalline schists. The dynamic factor is dominant at low temperatures and the thermal at high temperatures. Heat and stress both promote recrystallisation, but the latter exerts a powerful influence both in deforming the rocks and in determining the production of new structures. Many minerals are characteristic of rocks formed by dynamothermal metamorphism as contrasted with those produced by contact or thermal metamorphism. Some, indeed, are found only in the former, and others, although common to both types of metamorphism, are of less frequent occurrence in thermally-metamorphosed rocks, and, when they do occur, are found at a more advanced stage in the progressive metamorphism. Such minerals have been called *stress* minerals. Shearing stress favours, for example, the formation of kyanite, staurolite, chloritoids, minerals of the epidote-zoisite group, amphiboles, chlorite, sericite, and muscovite. In general the minerals developed under stress conditions are orientated at right angles to the direction of greatest pressure and schistose structures predominate. In the higher grades of metamorphism, however, there is a tendency in many rocks towards a segregation of the constituent minerals, leading to the production of foliated, gneissose structures.

In areas in which the regional metamorphism is of the dynamothermal type—just as in thermal metamorphism—it has been found possible to map zones of progressive metamorphism, marked by the successive appearances of particular index-minerals. Barrow, who was a pioneer in this type of investigation, applied the method with great success in his studies of the progressive metamorphism of the south-eastern Highlands of Scotland, and equally interesting results have been obtained by Goldschmidt and T. Vogt in their researches on the metamorphic rocks of the Caledonian mountain chain in Norway.

Argillaceous Rocks.—We have already seen that the formation of clay-slate even by pure dynamic metamorphism involves very often a considerable amount of crystallisation of minute micas, chlorites, and iron oxides. With rise of temperature the clay-slate passes first into phyllite, in which the cleavage planes become glossy in appearance from the development of visible flakes of mica, and then into mica-schists or even into micaceous gneisses, in which the micas attain still larger dimensions. Other aluminous silicates which are developed include chlorites, almandine garnet, staurolite, sillimanite, and the typical stress minerals, chloritoids and kyanite. Carbonaceous shales are transformed into graphite-schist. Barrow, who utilised argillaceous types of rock in working out the progressive metamorphism of the south-eastern Highlands, recognised the following zones :—(1) *Zone of digested clastic micas*; (2) *Biotite-Zone*; (3) *Garnet-Zone*; (4) *Staurolite-Zone*; (5) *Kyanite-Zone*; (6) *Sillimanite-Zone*. Characteristic rocks in the first zone are chlorite-sericite-schists, and, because chlorite is a conspicuous mineral in most of the rocks, Tilley later renamed this zone the *Chlorite-Zone*. In the garnet-zone the characteristic variety of garnet is near almandine in composition, and for this zone Tilley has suggested the name *Almandine-Zone*, since other varieties of garnet sometimes appear at earlier stages of the metamorphism. Chloritoids occur in the Biotite-, Almandine- and Staurolite-Zones. The various index-minerals are not confined to the zones to which they give their names, but normally persist in higher zones.

Arenaceous Rocks.—The transformation of highly quartzose sandstones and grits with inconsiderable amounts of argillaceous cementing material leads, in the lower grades of metamorphism, to the production of quartz-schists and schistose grits, in which the matrix is completely recrystallised to aggregates of sericite, chlorite, and quartz, while the larger grains of quartz show cataclastic effects, parallel orientation and a certain amount of deformation. With rising temperature and increased mobility of the quartz the rocks lose to a large extent their parallel structures and assume the granoblastic structure of typical quartzites. The more feldspathic types give rise to granulites. When the sandstones and grits contain much argillaceous cementing material, dynamothermal metamorphism brings about transformations similar to those met with in argillaceous sediments and results in the production of such rocks as quartz-mica-schist, quartz-garnet-mica-schist, staurolite-kyanite-gneiss and sillimanite-gneiss.

Calcareous Rocks.—Pure limestones and dolomites recrystallise as marbles in which the only constituents are calcite and dolomite, pressure preventing the dissociation of the double carbonate to give pencatite. In the case of impure limestones and dolomites and calcareous shales the transformations brought about by thermal and dynamothermal metamorphism respectively are often markedly different. As Harker has shown, the reactions characteristic of thermal metamorphism may be entirely suspended or may not proceed to completion. Quartz, for example, may crystallise alongside calcite even in very high metamorphic grades, and it is only rarely that wollastonite appears in rocks formed by dynamothermal metamorphism. Characteristic of the metamorphism of impure limestones and dolomites are lime- and magnesia-bearing silicates which are stress minerals, such as zoisite, tremolite, and actinolite. In the case of calcareous shales free from chloritic material, the formation of lime-bearing silicates is suppressed, and the resulting rocks are calcite-mica-schists and calcite-garnet-mica-schists. When chloritic material is fairly abundant in the original rock, as often happens, the rocks produced in the lower grades are calcite-chlorite-sericite-schists. With increasing metamorphism, however, and associated with the appearance of biotite, the calcite begins to take part in the chemical reactions with the formation of epidote and zoisite to give rise to calcite-epidote-mica-schist and calcite-zoisite-mica-schist. In the garnet-zone calcite enters still more largely into new mineral combinations and green hornblende is abundantly developed in the resulting rocks, which are calcite-hornblende-schists. With still more advanced metamorphism lime-rich feldspars appear. Whether free calcite will appear or not in the resulting rocks depends on the amount of the carbonate present in the original rock. If it has been in small amount the rocks produced will not contain free calcite and are represented by such types as epidote-mica-schist and zoisite-mica-schist; or, if chloritic impurities have been very abundant in the calcareous shales, the metamorphosed representatives are, with increasing grade of metamorphism, chlorite-schists (with or without calcite), epidote-chlorite-schists, hornblende-biotite-schists, and hornblende-schists.

Igneous Rocks.—The most noteworthy and characteristic feature in the dynamothermal metamorphism of acid igneous rocks is the breaking-down of the alkali feldspars with the formation of white micas and quartz. Thus, from rhyolites, felsites, and quartz-porphyries are derived sericite-schists. The process, however, is a reversible one, and in higher grades of metamorphism the resulting rock may take the form of a muscovite-biotite-granulite. Granites are changed to quartzo-feldspathic gneisses, often with the development of minerals such as garnet, which were not present in the original rock; they show also pronounced "flaser" and "augen" structures. When we turn to basic igneous rocks, we find that the characteristic mineral transformations in the lower grades of metamorphism are the development of chlorite, albite, calcite, and epidote at the expense of the augite and labradorite of the original rocks. The rocks usually formed are calcite-albite-chlorite-schist and albite-epidote-chlorite-schist. Increasing metamorphism is marked by the coming in of hornblende and the production of hornblende-schists, and, in the highest grades, hornblende-gneisses. Garnet is a frequent, and often abundant, constituent of these hornblendic types. Not infrequently the larger basic igneous masses have undergone the mineralogical transformations described above while retaining in large measure their original igneous structures. This may have been due in some cases to effective resistance to shearing; in other cases it has happened in areas where there is reason to suspect that the shearing stress failed in intensity. Ultrabasic igneous rocks, which are richer in magnesia and poorer in lime than basic rocks, are transformed into antigorite-schist, talc-schist, tremolite-schist, and anthophyllite-schist.

(*d*) **Plutonic Metamorphism.**—The earliest attempt to explain the phenomena of regional metamorphism was made by Hutton—the eminent Scottish geologist—who maintained that the crystalline schists were originally aqueous sediments which had been gradually deposited upon the floor of the ocean. When a great thickness of strata had accumulated, the loose sediments were supposed to have been consolidated by the pressure of the overlying masses. The internal heat of the earth next began to "soften" the compressed strata, and even eventually to melt them. Hutton supposed that granite and other plutonic masses represented those portions of the strata which had actually been melted, while those portions which had only been "softened" by the "internal fire" now constituted, according to him, our crystalline schists. Thus Hutton's theory of *plutonic metamorphism* does not, after all, differ essentially from that of contact metamorphism, for, according to the former, the heated interior of the earth seems to have played the same rôle as a batholith.

Plutonic metamorphism in the modern sense, however, implies changes produced at considerable depths in the earth's crust by great heat and uniform pressure. The heat is supposed to be maintained by the increase of heat in depth and by magmatic heat. Because of the absence of directed pressure and the great depths at which the metamorphism has taken place, the new minerals formed are anti-stress minerals of small specific volume and high density. In contrast with the products of dynamothermal metamorphism the rocks show characteristically granulitic rather than schistose and other parallel structures. Most of the rocks which have been claimed as the products of plutonic metamorphism occur in the Archæan complexes in many parts of the world. They include quartzites, cordierite-, sillimanite- and garnet-gneisses, and marbles—types derived from sedimentary rocks; acid granulites formed from quartzo-feldspathic sedimentary or igneous rocks; and pyroxene-granulites, pyroxene-gneisses, eclogites, garnet-amphibolites, etc., formed from basic igneous rocks.

The study of gneisses of composite origin—injection gneisses—and the evidence which has been adduced as to the soaking of rocks by magmatic solutions have led some workers to claim that the recrystallisation of metamorphic rocks of deep-seated origin must be ascribed in considerable measure to the action of emanations from subjacent batholiths. Heat, directed pressure, uniform pressure, and emanations from igneous magmas are all doubtless important factors in bringing about metamorphism. The metamorphism of rocks, however, particularly in areas which have undergone several superposed metamorphisms, still presents countless unsolved problems, and much research, as well physical and chemical as geological, remains to be carried out before an adequate conception of the subject can be attained.

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CHAPTER XVI

ORE-FORMATIONS

Syngenetic Ore-Formations—Native Metals and Ores in Igneous Rocks; Ores in Bedded Rocks (Chemical Precipitates, Clastic Ores, Ores in Schists). Epigenetic Ore-Formations—Fissure Veins or Lodes; Nature of Fissures; Width and Extent of Lodes; Simple and Complex Lodes; Transverse and Coincident Lodes; Systems of Lodes; Branching and Intersection of Lodes; Heaving of Lodes; Contents of Fissure Veins; Structure of Fissure Veins; Outcrop of Lodes; Gossans; Association of Ores in Lodes; Succession of Minerals in Lodes; Walls of Lodes; Stockworks; General Remarks on Fissure Veins.

ORES are metalliferous minerals or mixtures of such minerals, in which the proportion of metal is often sufficiently large to admit of its being profitably extracted. The term "metal" is here used in a conventional (not in a chemical) sense, and does not, therefore, apply to the metals of the alkalies and alkaline earths, but only to the "heavy" metals of commerce, viz.: gold, silver, platinum, copper, tin, lead, zinc, iron, manganese, nickel, cobalt, chromium, mercury, antimony, bismuth, etc.

Classification.—As one kind of ore-formation frequently passes into another, while considerable doubts obtain as to the genesis of many ores, it is hardly possible to devise a scheme of classification to which exception cannot be taken. For purposes of description, however, ore-formations may be grouped under these two main divisions:—1. **Syngenetic** or **Contemporaneous**, and 2. **Epigenetic** or **Subsequent.**

I.—SYNGENETIC ORE-FORMATIONS

These are formations of the same age, broadly speaking, as the rocks in which they occur or with which they are immediately associated. Some of them appear in igneous rocks, while others are associated with derivative, and yet others with metamorphic, rocks.

1. ORES OCCURRING IN IGNEOUS ROCKS

Ores of this class are original or primary constituents, appearing sometimes as isolated grains or crystals, disseminated through the body of a rock; at other times, as larger or smaller aggregates or masses which have obviously separated out from a molten magma. Not only ores but native metals occur under these conditions, more especially in plutonic basic igneous rocks. Acid plutonic rocks, on the other hand, are seldom rich in such constituents.

(1) **Native Metals.**—Iron is irregularly disseminated through the basalt of Ovifak (Disco Island, West Greenland) in the form of scales, grains, nodules, and larger lumps and masses. Nickel-iron, in small grains, is met with in olivine gabbro, peridotite and serpentine in South Island (New Zealand). Platinum also occurs in similar small grains in ultra-basic igneous rocks, such as peridotite, dunite, and serpentine in the Ural Mountains, and in British Columbia. Gold, silver, copper, etc., have likewise been detected, generally as minute inclusions, in the constituent minerals of various igneous rocks—never in sufficient quantity, however, to invite mining operations.

(2) **Ores.**—These are oxides and sulphides—the former being represented chiefly by magnetite, ilmenite, and chromite; and the latter by pyrite, pyrrhotite, and chalcopyrite—each of which may contain variable percentages of nickel and cobalt.

Oxides. Magnetite, often titaniferous, is one of the commonest and most widely diffused constituents of igneous rocks. Now and again it forms massive aggregates in plutonic basic eruptives, as in certain gabbros, and gabbro-diorites in Sweden, Finland, Norway, and North America. In these rocks the mineral occurs disseminated in the usual way, along with other accessory constituents, but is so abundant as sometimes to constitute a large percentage of the rock. Here and there, indeed, it becomes concentrated so as to form enormous aggregates. In some cases these aggregates are sharply marked off from the igneous rock in which they lie; in other cases, the disseminated ore gradually becomes more and more abundant at the expense, so to speak, of the other constituents of the gabbro, so that there seems to be, as it were, a passage from the latter into the ore-aggregate. Such aggregates are usually rich in ferromagnesian minerals (hornblende, rhombic pyroxene, and olivine), which are not infrequently accompanied by biotite, apatite, green spinel, and various sulphides (pyrite, pyrrhotite, and chalcopyrite). Ilmenite occurs in some Norwegian gabbros under similar circumstances

(Fig. 92), the ore-aggregates either forming an abrupt junction with the mother-rock or graduating into it in the same way as titaniferous magnetite. Chromite is a frequent constituent of peridotites, and now and again so largely abounds that the rock containing it is mined. At Hestmandö, in Norway, for example, the rock exploited is composed essentially of olivine, enstatite, picotite, and chromite. Tin-ore (cassiterite) likewise occurs as a primary constituent of many granites, but only in scattered grains and thin veins. It has never been mined in these rocks, but this is probably one of the sources of the tin-ore of "placers."

Sulphides. Pyrite and pyrrhotite appear now and again as ingredients of certain igneous rocks, and chalcopyrite has also been recorded as occasionally occurring under similar conditions. While, in some cases, such metallic sulphides may be of secondary origin, there seems no reason to doubt that they are frequently primary constituents of the rocks in which they appear. It is highly probable, therefore, that the massive aggregates of sulphide ores met with in certain plutonic rocks are examples of magmatic segregation, and as truly syngenetic as the magnetic and titaniferous iron-ores referred to above. In some of the Norwegian gabbros, pyrrhotite, pyrite, and chalcopyrite, each containing a variable percentage of nickel and cobalt, are disseminated in small grains through the rock, but now and again they have segregated to form large masses of irregular form, which are grouped chiefly along the line of junction between the gabbros and the adjacent rocks (see Fig. 93). Similar examples of the magmatic segregation of nickeliferous sulphide-ores are met with in Sweden, Piedmont, and North America. It is believed by some authorities that the auriferous pyrite of Rossland, British Columbia, and the high-grade copper-ores occurring in the peridotites and serpentines of northern Italy have originated in the same way.

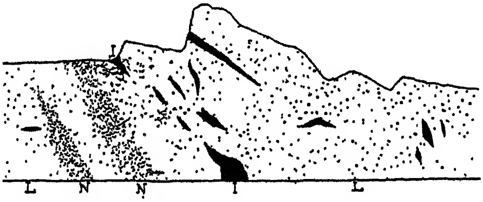


FIG. 92.—SECTION AT BLAAFJELD. (Vogt.)

L, Labradorite-rock; N, Norite-pegmatite; I, Ilmenite. Length of Section 600 metres.

The labradorite-rock (gabbro) contains some 2 per cent. ilmenite, 4 per cent. ferromagnesian minerals, and 94 per cent. feldspar; the norite-pegmatite yields 40 per cent. ilmenite, 35 per cent. ferromagnesian minerals, and 25 per cent. feldspar. Where the norite-pegmatite graduates into the labradorite-rock, the percentages are as follows: 6 to 18, ilmenite; 8 to 16, ferromagnesian minerals; and 56 to 66, feldspar.

2. ORES OCCURRING IN BEDDED ROCKS

Under this head are included precipitates from aqueous solution, certain alluvial deposits, and ores interstratified with crystalline schists.

(1) **Precipitates from Aqueous Solution.**—The most important ores of this origin are iron- and manganese-ores. The iron-ores in question are well represented by the formations now taking place in marshy land and lakes. These consist essentially of hydrated ferric oxide, but they usually contain many impurities. Sometimes they form continuous beds; in other places they occur as nodular concretions of some size, or as aggregates of oölitic and pisolitic spherules. They are the products of the alteration of ferriferous minerals and rocks, and owe their origin mainly to the action of water containing organic acids, which act as powerful solvents of iron-salts. Rocks exposed to the action of such acidulated water are bleached white by the removal of their iron, which is carried away in solution as a bicarbonate. From this solution, the iron tends to be precipitated as ferric hydrate, unless much decomposing organic matter be present; when such is the case oxidation is prevented, as the iron is then thrown down as a carbonate. The pisolitic limonite forming in the shallow waters of many existing lakes, and the earthy bog iron-ore so frequently present in swampy land, are good examples of this class of ore-formations. Bedded iron-ores (both oxides and carbonates) are met with in many geological systems—ranging from post-Tertiary to Palæozoic horizons. While many of these are of freshwater or brackish-water origin, others are marine. As examples may be cited, the lake- and bog iron-ores of Finland, Scandinavia, Holland, and other countries in North Europe—all deposits of Recent age;

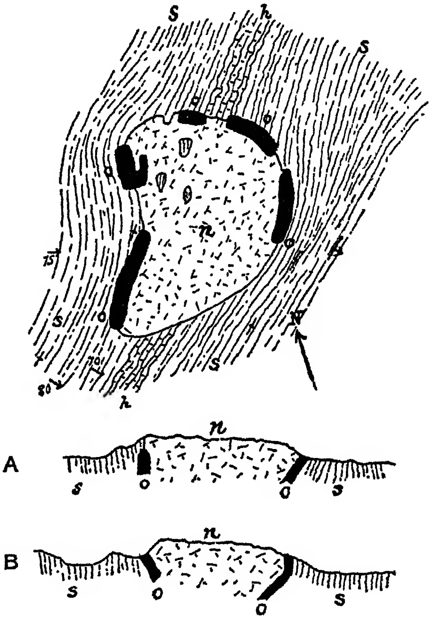


FIG. 93.—SKETCH-PLAN OF MEINKJÄR, NORWAY. (After Prof. Vogt.)

s, gneissose rocks; *h*, hornblende-schist; *n*, norite with inclusions of gneiss (xenoliths); *o*, ore; A, B, sections across the area, from east to west.

the Mesozoic limonites and earthy carbonates of the Lias, the Great Oölite, the Wealden, and the Lower Greensand, in England; and the clay ironstones which are so abundantly developed in the Carboniferous system of this and other countries (Fig. 94). Most of the ironstones last referred to appear to have been formed by direct precipitation in lakes and lagoons. In the case of the nodular concretions met with in the same series of strata, we have examples of the subsequent concentration or aggregation of ferruginous matter, originally diffused through the beds in which such nodules occur.

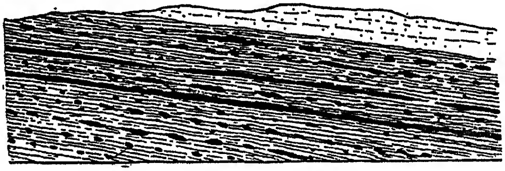


Fig. 94.—Seams and Nodules of Clay-ironstone in Carboniferous Shales.

Manganese ores (pyrolusite, psilomelane, wad) are not so abundantly met with as iron-ores. They occur, however, under similar conditions amongst sedimentary rocks of all ages, sometimes as concretionary nodules, at other times in layers and beds, which are not infrequently pisolitic.

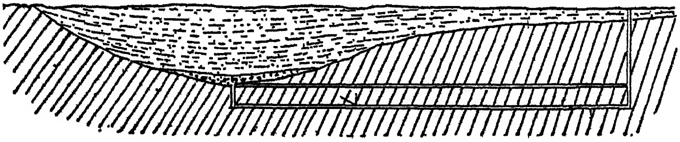


Fig. 95.—Section of Auriferous Lead (or Placer) on the Lower Murray, near Corowa. (After E. F. Pittman.)

(2) **Clastic Ore-Formations.**—These are alluvial deposits, derived from the disintegration of metalliferous rocks and ore bodies of various origin, and are known to mining men as *Placers* (Fig. 95). The metals obtained from such deposits are chiefly gold, platinum, and tin. The beds vary much in character, consisting, in some places, of coarse gravel and shingle, or of finer gravel, grit, and sand. Most placers are of Recent and Pleistocene age, and are usually more or less

unconsolidated. Many, however, occur in the Tertiary system, while a few date back to Mesozoic, and some even to Palæozoic times. These older deposits are, as a rule, consolidated, forming coarse grits and conglomerates. The metals and ores of highly porous placers are usually concentrated in the bottom layers. In the case of finer-grained alluvia, however, they may be sparingly scattered through the whole thickness of the deposits. Should the bed-rock underlying a placer be more or less fissured and shattered, the metal or ore not infrequently finds its way down for a few inches into cracks and crevices. While the gold occurring in quartz-veins, etc., is often intimately associated with metallic sulphides, such as iron-pyrite, the gold met with in placers is usually in the free state. During the processes of disintegration and denudation, the sulphides containing the gold are gradually dissolved, and the process of solution is carried on in the placer itself, so that sooner or later the gold becomes freed from its baser associates. The crystalline surfaces occasionally presented by placer-gold, and the usually smooth and unscratched appearance of the nuggets, are suggestive of chemical deposition. Many mining men, indeed, believe that nuggets grow by slow accretion.

Placers being of fluviatile origin, it will be readily understood that such formations can seldom be of great geological antiquity. Terrestrial accumulations are only exceptionally preserved—the Mesozoic and Palæozoic systems consist for the most part of marine formations. The further back we trace the geological record, therefore, the scantier become all traces of old land-surfaces. Lacustrine and fluviatile deposits of Tertiary age have now and again been preserved, under lava, as in California and Victoria (Australia). The auriferous gravels of these regions are believed to be river-gravels belonging to the Pliocene. They are often more or less hardened by infiltration of silica, ferruginous matter, etc., and constitute the " deep leads " of the miners. The shallow placers of the same regions are of recent age—derived in considerable measure from the denudation of the older series. The alluvial deposits of the Ural Mountains, which yield both gold and platinum, the " stream-tin " (cassiterite) accumulations of Cornwall, which are now practically exhausted, and the alluvial tin-fields of Malaysia, from which so much of the world's output at present comes—are all examples of the same class of ore-formations. Placers of older date than the Tertiary are of rare occurrence, only a few gold-bearing conglomerates having been met with in Mesozoic and Palæozoic systems, and these are seldom rich enough to be worked.

(3) **Ores occurring in Metamorphic Rocks.**—Ores of iron and manganese are the most frequently occurring formations met with as beds interstratified with schistose rocks. It is sometimes difficult to distinguish such syngenetic formations from certain epigenetic formations known as "bedded veins," and of which some account is given in the sequel. Usually, however, a bedded ore is not so sharply marked off from the schists among which it lies, as is the case with a true vein. The bedded ore does not traverse overlying and underlying schists, nor does it send out veins. It behaves, in short, like a truly contemporaneous bed—following all the flexures, folds, and crumplings of the series in which it occurs. The thickness of such beds varies indefinitely: they are usually lenticular, and thicken and thin out to many feet or even yards. In Sweden the bedded ores are usually more or less closely associated with crystalline limestone, or with a rock consisting mainly of pyroxene and amphibole, and often containing garnet and epidote. Iron-ores are obtained from similar schistose rocks in Norway.

Beds of magnetite and specular iron are associated with schistose rocks in many other countries, as in S. Russia, in the Riesengebirge, in Spain, in the United States (New York, New Jersey, Carolina, Michigan), and elsewhere. Carbonate of iron (siderite) is another ore met with amongst schistose rocks. Manganese ores likewise occur under similar conditions in Sweden, Bukowina, Brazil, and the United States of N. America.

II.—EPIGENETIC ORE-FORMATIONS

The formations included under this head are of later age than the rocks with which they are associated or in which they occur. They have been subsequently introduced into the positions they now occupy, and thus a large number appear in fissures and other cavities in rocks of all kinds, while in many cases they replace pre-existing minerals and rock-masses. They may be grouped as fissure-veins or lodes, bedded veins, and irregular formations. This is not a very satisfactory classification, for one and the same ore-deposit may assume many different forms in its course, appearing sometimes as a "lode," sometimes as a "bedded vein," or as one or other of the "irregular formations." Nevertheless, the classification here adopted serves to bring prominently into view the various conditions under which the epigenetic ore-formations occur.

I. FISSURE-VEINS OR LODES

Nature of Fissures.—An ore-vein or lode may be defined as a rent or fissure filled with metalliferous and other minerals alone, or with rock-débris in addition. The fissures in which true lodes occur are often mere chinks or wider clefts, along which no rock-displacement may have been effected. Narrow fissures of this kind may occur singly, but often quite a large number, occupying parallel or nearly parallel positions, traverse the rocks in some given direction. None of these may show slicken-sides or yield any evidence of slipping or faulting. Not infrequently, however, the fissures occupied by lodes are faults, although it would seem that the amount of rock-displacement (when that can be measured) is seldom very great—not often exceeding two or three hundred feet, and being usually much less. Many ore-bearing faults, however, traverse highly disturbed and schistose rocks, and the amount of displacement in such cases must be quite conjectural. Be that as it may, it would appear that the larger dislocations occurring in a region rich in lodes are seldom ore-bearing. The faults occupied by lodes may be normal or reversed. Few lodes are quite vertical, but the great majority approach verticality—the inclination from the vertical being termed the *hade* or *underlie*. The rocks traversed by a lode are known as the *country* or *country-rock*; and the wall of the fissure which overhangs the miner when standing upright is termed the *hanging-wall*; while that on which he stands is the *foot-wall* (see Fig. 96).

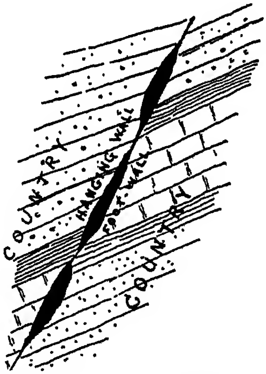


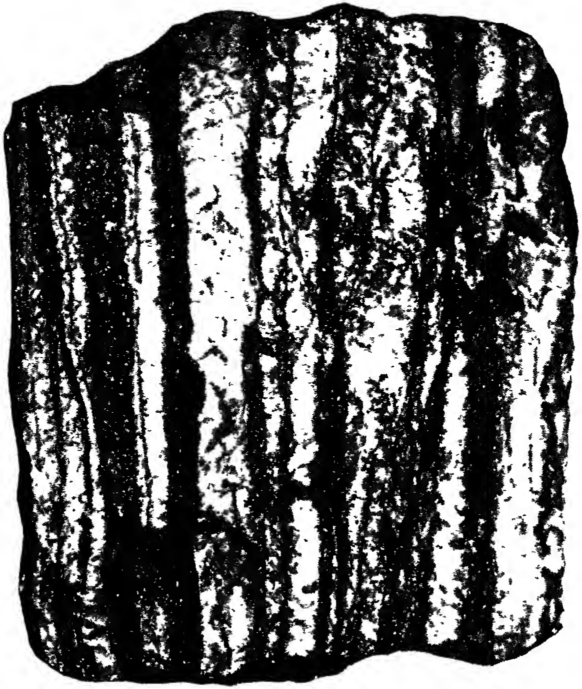
FIG. 96.—FISSURE-VEIN OR LODE.

Width and Extent of Lodes.—Individual lodes often vary much in width—the walls of the fissure approaching and receding in an irregular manner, and now and again being in close apposition, in which case the lode is, of course, "nipped out." Such irregularities, it need hardly be said, are due to the character of the original fissure, except when limestone forms the wall or walls of a lode. In such cases the irregular width of the cleft has not infrequently been caused by the unequal dissolution of the rock. Some lodes are very narrow—a few feet or less—others may exceed 100 feet in width. In the case of very broad lodes, however (say, from 20 feet to 100 feet), it must be understood that this is not the actual width of the original fissure, but includes as much of the adjacent rock as contains ore in payable quantity—whether occurring as impregnations or as strings, threads, veinlets, and *flats* (see pp. 253, 255). Some broad lodes, for example, consist of more or less numerous and approximately parallel veins, occupying very narrow fissures or mere cracks, which in the central portion of the "lode" are often less than an inch apart, but become more widely separated towards the limits of the fissured area. Lodes of this kind are known as "sheeted zones," and sometimes attain a width of 100 feet or more. A "sheeted zone," therefore, is simply a belt of highly fissured rock, which, when gold is present in the fissures, may be profitably extracted so long as the veins are rich enough or sufficiently numerous.

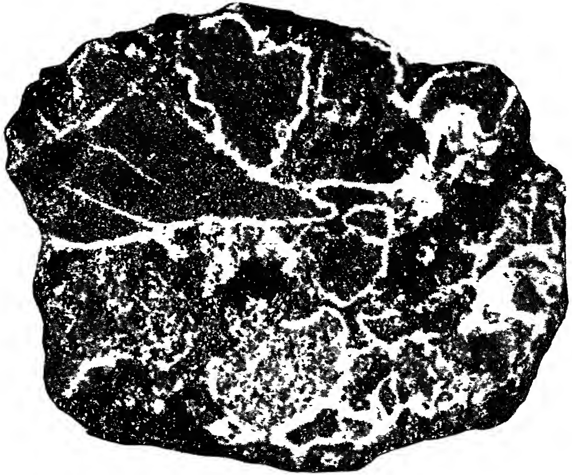
Lodes differ considerably in length or lateral extent. Some die out in much less than a mile, while others have been followed for great distances. Probably the longest known is the auriferous "Mother Lode" of the Sierra Nevada, California, which runs in a relatively straight line for more than seventy miles.

The longest veins seem usually to have the greatest vertical range. Some of these have been followed to depths not far short of 3000 feet, without showing any appearance of dying out. Many of the shorter veins wedge out downwards or upwards. Lodes of this kind are frequently very irregular—branching often in many directions. Some wedge out simply; others, again, divide into two or more smaller and gradually diminishing veins; or they may break up into a perfect network of strings and veinlets.

Simple and Complex Lodes.—A lode is said to be *simple*



1. Portion of a Lamellated Lode or Metalliferous Vein. The dark bands are ore, the white bands "veinstone." Two-thirds natural size.



2. Portion of Brecciated Lode. The white portions are "veinstone"; the irregular-shaped areas surrounded by thin white bands (veinstone) are fragments of "country-rock." The intermediate dark areas are mostly ore. Nearly natural size.

[*To face page* 240

when it occupies one single well-defined fissure (see Fig. 97). Often enough, however, the formation of a fissure has been accompanied by much rock-shattering, the adjacent rocks being confusedly jumbled and crossed in every direction by numerous branching cracks and crevices. When all these cavities are filled with mineral matter we have a *complex* lode (see Fig. 98). One and the same lode may be simple in one part of its course and complex in another. This is not infrequently the case when a lode traverses rocks of very different kinds. For example, a vein may be simple while passing through rocks which have yielded readily to tension,

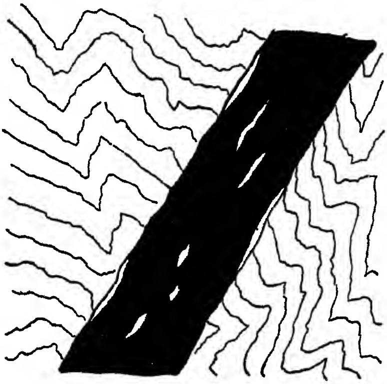


FIG. 97.—SIMPLE LODE SHOWING MASSIVE STRUCTURE.

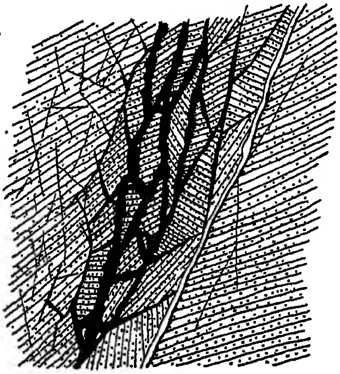


FIG. 98.—COMPLEX LODE. (After R. Beck.)

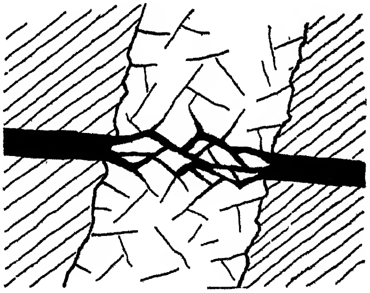


FIG. 99.—LODE DIVIDING AND BRANCHING IN IGNEOUS ROCK. (Plan.)

but becomes complex when it begins to traverse some massive irregularly jointed rock (see Fig. 99).

Transverse and **Coincident Lodes.**—Lodes cutting through stratified rocks usually cross the planes of bedding at an angle, and are then said to be *transverse* (see Fig. 100). Now and again, however, especially when the strata dip at a high angle, a lode may coincide with the planes of bedding. The epigenetic character, however, is usually apparent, the lode not being strictly confined between two bedding-planes, but here and there invading both overlying and underlying strata (see Fig. 101).

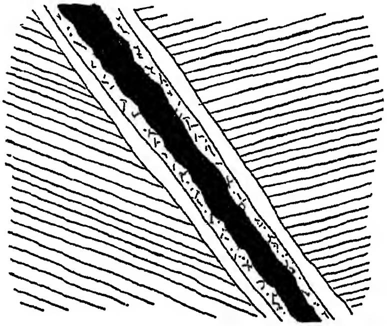


Fig. 100.—Transverse Lode. (After R. Beck.)

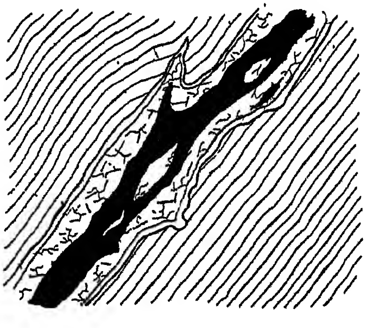


Fig. 101.—Coincident Lode. (After R. Beck.)

Systems of Lodes.—While lodes often occur singly, it is more frequently the case that several or many are associated so as to form one or more systems. Their general disposition recalls that of the basalt-dykes described in Chapter XIII. Like these, they trend in certain definite directions, some appearing in true faults, others in simple rents or fissures. In certain regions only one such system may be present; in other places two or more systems may appear, one set crossing another. As the fissures and faults in which they occur are the result of crustal movements, it is not surprising that groups of parallel lodes should often bear a definite relation to the principal folds and flexures of a region. Some, therefore, coincide with the average strike of the country-rock, while others traverse the strike more or less at right angles. In mountain tracts lodes not infrequently run parallel to the general axis of elevation. Hence, if the date of the elevation be known, the age of the faults and fissures is at once determined. As crustal movements have often affected the same area at different periods, and not infrequently in different directions, new systems of divergent and intersecting folds and fissures have successively been produced, the relative age of which can usually be ascertained by observing the behaviour of one system to another.

Branching and Intersection of Lodes.—Lodes not infrequently divide into two or more branches, which, after pursuing separate courses for longer or shorter distances again come together (see Fig. 102). Occasionally, also, two lodes may gradually converge until they meet, and then, after running side by side for some little way, may again diverge (see Fig. 103); or, instead of diverging, one may

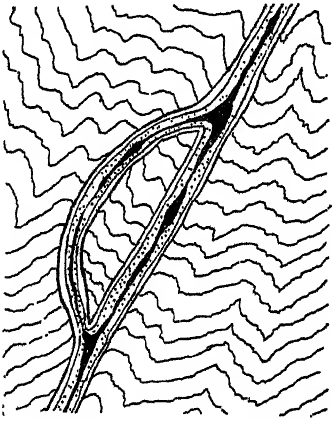


FIG. 102.—LODE DIVIDING AND RE-UNITING.

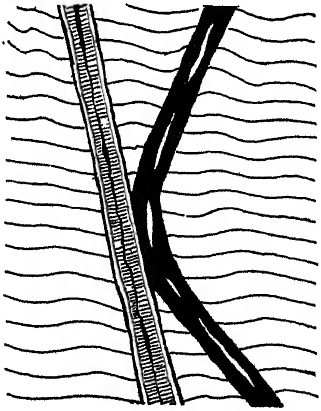


FIG. 103.—LODES CONVERGING AND DIVERGING.

intersect the other without displacing or shifting it, and subsequently resume its original direction (see Fig. 104). In such a case the fissure occupied by the intersecting and therefore younger vein is obviously a simple rent and not a true fault. Occasionally, two veins meet at approximately right angles, the younger similarly intersecting the older without displacing it (see Fig. 105). Very rarely two fissures intersecting at

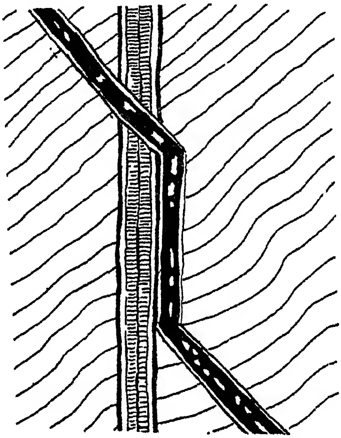


FIG. 104.—LODES CONVERGING AND INTERSECTING

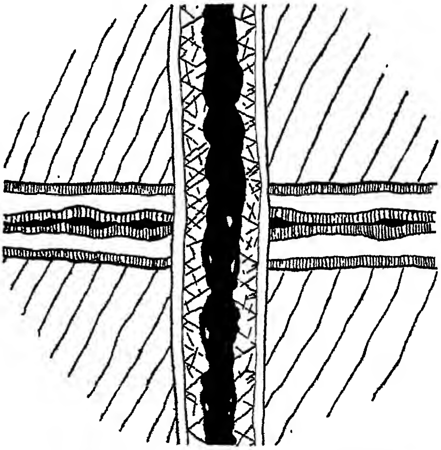


FIG. 105.—LODES INTERSECTING AT RIGHT ANGLES WITHOUT DISPLACEMENT. (Plan.)

right angles have received their mineral contents at the same time (see Fig. 106).

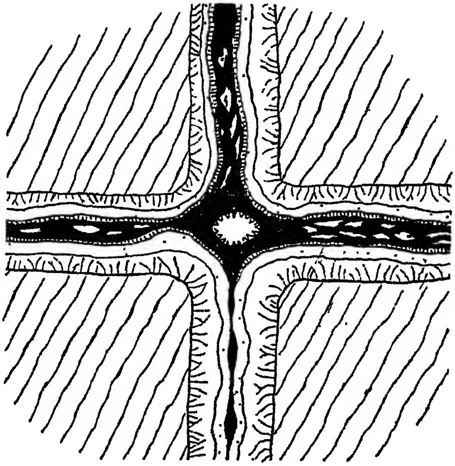


Fig. 106.—Contemporaneous Cross-veins. (Plan.)

Heaving of Lodes.—When the intersecting lode occupies a fissure of displacement or true fault, it invariably shifts or heaves the lode it traverses (see Fig. 107). If the fault be normal, then the older lode is shifted in the direction of the downthrow; in the case of a reversed fault the older lode will, of course, be heaved in the opposite direction.

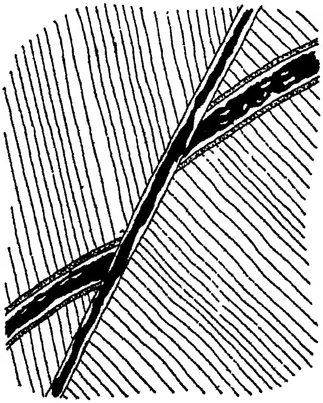


Fig. 107.—Heaving of one Vein by another.

Contents of Fissure-Veins.—These are known as *veinstone*, *veinstuff*, *matrix*, or *gangue*, and consist largely of crystallised minerals, such as quartz, calcite, and other carbonates (dolomite, magnesite, etc.), barytes, and fluor-spar. Fragments of the "country" (*i.e.* the rocks traversed by a lode) frequently appear, and often constitute the larger portion of the veinstuff. The fragments are of all shapes—angular, subangular, or rounded—and some of them may show smoothed and striated surfaces. They vary also in size, from large blocks down to finely comminuted particles. The ores are irregularly distributed through the veinstone as grains, crystals, patches or bunches, laminæ, threads and strings, often crossing and recrossing. Sometimes they assume the form of vertical or steeply inclined columnar or chimney-like aggregates, surrounded on all sides by lean or barren veinstuff. Such rudely columnar ore-bodies are known as *shoots*. Or they may appear in the form of more or less regular plates and tabular sheets, disposed in parallel positions with similar plates of veinstones; or, again, they may occur as massive aggregates occupying the whole fissure to the exclusion of any veinstuff. On the other hand, ore may be entirely wanting in some parts of a lode, the fissure being either filled with veinstone and rock-rubble only, or closed by the apposition of its walls.

Structure of Fissure-Veins.—(*a*) MASSIVE STRUCTURE. When a fissure is entirely filled with ore, or with crystallised or cryptocrystalline mineral matter containing ore disseminated through it, the structure is said to be massive (see Fig. 97, p. 241). Galena (lead-ore), for example, is often met with completely filling fissures—crystallised veinstone being either entirely absent or occurring only as small inclusions in the ore, or as a meagre interrupted layer lining the walls. Auriferous quartz-veins are an example of the same structure—the ore in this case being included in the quartz which wholly fills the fissure.

(*b*) PLATY, LAMELLATED, OR BANDED STRUCTURE.—In this structure the ore and the veinstone are disposed in more or less sharply defined sheets or layers parallel to the walls of the fissures (Plate LIX. 1). This is the commonest kind of structure met with in lodes. The sheets are of very variable thickness, and may be few in number, in which case some or all may be relatively thick; or they may be numerous and all extremely thin—mere laminæ of irregularly alternating ore and veinstuff. Now and again, however, they are arranged symmetrically in pairs. The opposite walls may each be lined, for example, with a layer of quartz or other veinstone; to this may succeed two bands of ore, one on either side——and such duplication may be repeated again and again, until the fissure is completely filled (Fig. 108). Such a banded lode is said to be *symmetrical.* The crystallised minerals are often prismatic—their longer axes being perpendicular to the walls and their pyramidal terminations directed towards the centre of the vein. A section across such a sheet has suggested to mining folk its resemblance to a comb, and thus we have the term *comby lode* applied to symmetrical fissure-veins. Frequently, the fissures are not completely filled—medial cavities of less or greater extent being left. These are termed *vughs* or *druses*; they are usually lined with crystallised minerals.

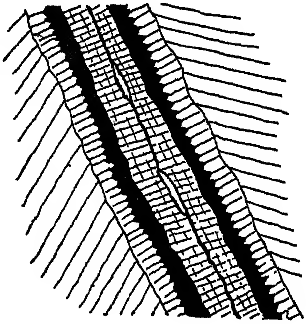


FIG. 108.—LAMELLATED LODE WITH DRUSES.

(*c*) BRECCIATED STRUCTURE.—Some lodes are largely brecciated—abundant fragments of mineral plates or lamellæ, together with pieces of the country-rock, being scattered through amorphous or irregularly crystallised veinstuff. This structure shows that the fissure occupied by a banded lode has been subsequently reopened—the crustal movement resulting in the fracturing and shattering of the platy layers of the original lode and the introduction into the reopened fissure of fragments of the country-rock. Later on, this jumbled mass has been permeated by metalliferous and mineral solutions, which have bound the débris together (see Fig. 109 and Plate LIX. 2). Now and

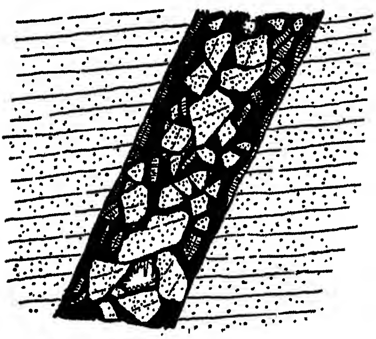


FIG. 109.—BRECCIATED LODE.

again these subsequently introduced ores and crystalline minerals, in place of being diffused through the débris, are found encrusting the embedded pieces of country-rock and fragments of older veinstone with successive layers, forming what are termed *ring ores* or *cockade ores* (Cocardenerze).

In some reopened and refilled veins the products of the first infilling have not been entirely broken up—the fissure has simply been widened and a new comby lode has been formed outside of and parallel to the original symmetrical lode. The reopening and refilling process has in certain cases been repeated several times, the lode consisting of a succession of duplicate sheets, each two or more bands representing a separate infilling (see Fig. 110). Many other structures may be observed in reopened fissure-veins. Occasionally, the new cavities are crowded entirely with rock-débris, which may or may not be ore-bearing. Now and again, however, the interstices and wider spaces between some of the larger blocks detached from the walls have not been completely filled with new mineral matter. In such cavities (or *vughs*) finely crystallised minerals and stalactitic formations frequently appear.

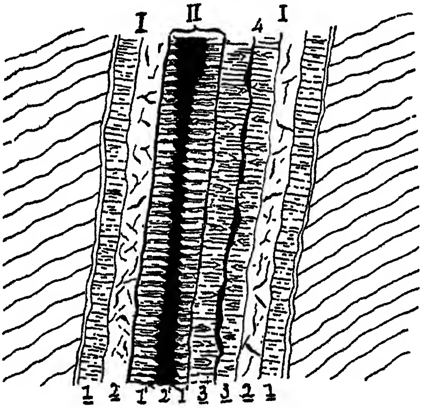


FIG. 110.—REOPENING AND REFILLING OF VEINS.

I—1, 2, I—1, 2, 3, 4, first infilling; II—1', 1', 2', second infilling.

Outcrop of Lodes.—The line along which a lode comes to the surface is variously termed *outcrop*, *outgoing*, or *back*. When a lode consists of more durable ingredients than the rock it traverses, as is frequently the case with quartzose lodes, it projects at the surface, and forms what miners term a *reef*. On the other hand, should a lode be less durable than the country-rock, its outcrop is revealed by a trench-like depression. Lodes, however, are often concealed underneath superficial deposits. Some, again, do not reach the surface—either owing to the dying-out of the fissures, or to the subsequent accumulation above the country-rock of later sedimentary or igneous formations. It is probable, indeed, that lodes exist in many unsuspected places—more particularly in regions where considerable unconformities occur. They are met with traversing rocks of all ages—Palæozoic, Mesozoic, and Cainozoic alike; but, as might have been expected, are of more frequent occurrence in Palæozoic than in Mesozoic, and in Mesozoic than in Cainozoic rocks. They are most commonly associated with metamorphic rocks and eruptive masses, although this is by no means invariably the case.

Gossans.—A lode at its outcrop is usually more or less weathered, and of a rusty brown, red, or yellowish colour from the frequent presence of ferruginous matter. Such weathered backs are termed *Gossans*. The thickness or depth of gossans is quite indeterminate. Sometimes they extend to a depth of many fathoms, but usually they do not go much below the water-level of a district. Native metals (gold, silver, copper), carbonates, sulphates, and phosphates of metals, and other metalliferous compounds often occur in relatively large proportion in gossans. All these are the products of the decomposition of the ores of the original or unaltered lode. As the lode is followed to greater depths, native metals and oxidised ores gradually disappear, and are succeeded by sulphides or other compounds devoid of oxygen. As the present surface at which lodes crop out must be far below that which existed at the time of their formation, it will be readily understood why metals such as gold and silver should often occur in relatively large proportion in the gossans of auriferous and argentiferous lodes. The outcrop of a vein is necessarily lowered with the general lowering of the land-surface by denudation. The chemical action of percolating water affects the metalliferous contents of the lode, which ere long become oxidised, and may even be reduced to the state of native metals. These last, owing to their superior weight and insolubility, are not washed away with the lighter and more soluble constituents, and thus tend to become concentrated in the gossan. This is the reason why the gossanous parts of auriferous and argentiferous lodes are usually richer than the underlying, unweathered portions. The richness of a gossan, therefore, is apt to deceive the unwary as to the value of the subjacent deposit—rich gossans having sometimes been found capping lodes which were too poor to work. When a gossan yields valuable metals or ores, it certainly indicates the presence of these in the lode below; but whether the latter is rich enough to be advantageously worked cannot be determined until the undecomposed material below the gossan has been carefully examined. The effect of percolating water can frequently be traced to a considerable depth below the "iron-hat"—or true gossan—the general result being a concentration of secondary products, consisting partly of oxides and partly of sulphides. This *secondary enrichment* of a lode sometimes extends to a depth of 600 feet or even 750 feet from the surface.

Association of Ores in Lodes.—The minerals in lodes often show paragenetic relations—that is to say, certain minerals are frequently found associated. For example, manganese- and iron-ores often occur together, and the same is true of galena (PbS) and zinc-blende (ZnS), of cobalt- and bismuth-ores, and of cobalt- and nickel-ores. In like manner the copper-sulphides (bornite and chalcopyrite) not infrequently are accompanied by iron-pyrite. Again, when bismuth glance (Bi_2S_3) is present, chalcopyrite is seldom or never absent. Similarly, pyrrhotite and chalcopyrite are constant associates. Once more, it is most usual to find fluor-spar, topaz, molybdenite (MoS_2), wolframite [$(Fe,Mn)WO_4$], and cassiterite (SnO_2) occurring together in the same ore-formation.

Succession of Mineral Deposits in Fissures, etc.—It is not hard to understand why ore-deposits should often seem to have preferred one rock to another. It is obvious, for example, that relatively hard, porous, and highly fissured rocks would be more readily traversed by solutions than soft impervious masses, in which joints and faults are apt to be close, and even approximately water-tight. Again, some rocks, particularly limestone, are more or less readily dissolved by acidulated water, and thus, in time, yield ample space for the deposition of such ores as galena and hæmatite. Very often, however, the large ore-bodies occurring in limestone are simply cases of metasomatic replacement. The precipitation of ores, indeed, would seem to have been frequently induced by chemical reaction between metalliferous solutions and the country-rock. If the latter contained carbonaceous matter, for example, this would bring about the deposition of sulphides from solutions of metallic sulphates. Precipitation might also be expected to occur in places where subterranean currents, differing in temperature and in the nature of their solutions, came together. Further, in the case of ascending currents it is obvious that gradually diminishing heat and pressure must have played a dominant rôle in determining the deposition of substances held in solution.

But when we study the succession of minerals in banded lodes, it must be admitted that no general law governing that succession can be recognised. We can only conjecture that the chemical composition of the solutions circulating through the fissures may have varied from time to time. Sometimes it would appear as if successive deposition had been determined by the relative solubility of the minerals. Frequently, for example, quartz lines the walls of a lode and is overlaid by calcite. Again, it is highly probable that the earlier deposits of ore in a lode may not infrequently have played the part of precipitants to later introductions. Thus copper solutions might be reduced by iron-pyrite, the reaction giving rise to the formation of chalcopyrite. It is well known also that the iron-pyrite of auriferous quartz-veins frequently contains gold. In short, it seems not at all unlikely that many of the common associations of ores referred to above may be the result of one ore having acted as the precipitant of another.

Even in one and the same lode the mineral succession may be repeated several times, showing that at intervals similar conditions have recurred again and again. As the same succession of minerals may appear in lodes filled at widely separated geological periods, while lodes of the same age may differ greatly as regards their contents and the order of mineral succession, it is obvious that the nature and arrangement of the ores and other minerals in lodes can tell us nothing as regards the geological age of the deposits.

So far as observations have yet gone, it would seem that differences of depth have had considerable influence on the deposition of minerals in lodes. In many regions where lodes are worked, the present surface of the ground must be several thousand feet or even yards below the surface that existed when those fissure-veins were filled. In other cases we have no reason to believe that any such excessive denudation has taken place. We have the opportunity, therefore, of studying ore-deposits which have been formed at very great depths, and comparing them with others of much less deep-seated origin. Professor De Launay has cited quicksilver-formations as an example of the latter—since they appear to be restricted chiefly to rocks of relatively recent geological age which have been traversed by eruptive masses. According to De Launay, they do not occur in regions of older rocks or associated with eruptives of great age, simply on account of the extreme denudation which those regions have experienced. The upper parts of the older lodes, which may have carried quicksilver, have long since been removed, along with the country-rock traversed by them, so that it is only the pyritic or deep-seated ore-formations which are now encountered in the lodes of profoundly denuded regions. Again, Professor Vogt has pointed out some remarkable differences between gold-, silver-, and lead-bearing veins of relatively recent age, such as those of Comstock, Potosi, Hungary, etc., and the much older lead-silver veins of Norway, Bohemia, the Erzgebirge, etc. In both cases the lodes are closely associated with eruptive rocks, and the country-rock has undergone much alteration, so that the conditions attending the deposition of the ores and veinstones in all the regions referred to appear to have been similar. The differences referred to by Professor Vogt have reference not only to the contents of the lodes, but to the changes which have been superinduced on the country-rocks; and these differences, according to him, indicate that the older have been formed at a greater depth than the younger veins. From his point of view, therefore, the latter, if they were followed downwards, would gradually assume the character of the former. Whether such would prove to be the case is, of course, conjectural, but Vogt's hypothesis is to some extent supported by the phenomena revealed in certain deep mines. In the Cornish mines, for example, after passing down through their gossans the lodes were found to carry copper-ore with some tin-stone; at a still greater depth, a zone of mixed tin-stone and copper-ore was encountered, and under that tin-stone almost exclusively. So, again, in lodes carrying silver-lead-zinc ores it has frequently been observed that the proportion of zinc-blende increases with the depth. It would seem, also, that in many manganese-iron formations the proportion of iron similarly increases downwards. But much additional observation and study will be required before the laws governing the genesis and deposition of ore-formations can be clearly comprehended.

Walls of Lodes.—Occasionally the walls of lodes are more or less slickensided—owing, doubtless, to the one being ground against the other. [The smoothed and slickensided stones which not infrequently occur in the contents of lodes have already been mentioned. These are probably in some cases fragments detached from the walls after the latter had been smoothed; in other cases, they may have been slickensided *in situ*, blocks and stones having been pressed and rubbed against each other during movements of the country-rock.] A layer of clay often occurs between a lode and the "country," forming a *salband* or selvage. In most cases this clay is simply the decomposed surface of the wall. The thickness of decomposed rock is very variable, sometimes hardly exceeding an inch or two, while in other cases the rock may be rotted for many feet or yards away from a lode. On the other hand, the walls have often been rendered excessively hard by the infiltration of silica. Many lodes as they are followed downwards show only one wall, usually the foot-wall. In place of a definite hanging-wall, we may have a considerable breadth of much shattered and jumbled rock, the fissures between the separate blocks and fragments being sealed-up with veinstone and ore (see Fig. 98, p. 241). In other cases walls may become obliterated, as it were, by the gradual passage outwards of veinstuff and ore, which seem to merge insensibly into the country-rock. In yet other cases no definite walls can be traced, and a central fissure may or may not be seen. This is often the case with *impregnations*, to which reference will presently be made. As a rule, when the fissure occupied by a lode is a normal fault, one or both walls are well defined. The rocks on the downthrow side of such a fault are often highly shattered, while those on the upcast side are usually not much broken. When such a fault, therefore, is subsequently occupied by an ore-formation, it is the hanging-wall rather than the foot-wall that tends to be ill-defined. When a lode shows no definite walls, the original fissure is more frequently a simple rent than a true fault.

The ores and veinstones of a lode frequently invade the country-rock not only as impregnations, but as sheets (*flats*) and subordinate veins. These may be looked upon as merely extensions of the lode. Sometimes they penetrate the country-rock along planes of bedding, of cleavage, or foliation; in other cases, they obviously follow the subordinate cracks and rents which so often accompany faults.

Stockworks.—Now and again a mass of rock which may consist of sedimentary, of igneous, or of schistose materials, may be very much jumbled or crushed, and traversed by an infinity of minute, reticulating joints and fissures. This shattering is not necessarily connected with faults or true displacements, but has often resulted from crustal stresses and strains. Again, igneous rocks tend to become more or less abundantly jointed while they are cooling and consolidating. All such fissures, whether due to crushing or contraction, are liable to be filled with subsequently introduced mineral matter. It has frequently happened, therefore, that jumbled rock-masses have been permeated by ore-bearing solutions to such an extent that the rock can be mined in successive floors, forming what is known as a *Stockwork* (see Fig. 111). The infinitely

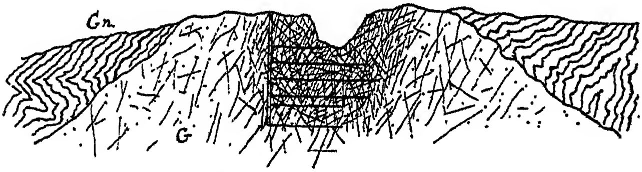


FIG. 111.—STOCKWORK.
Gn, gneiss, etc.; *G*, granite.

numerous veins, veinlets, strings and threads of ore branch and interlace often in a most confused and irregular manner, although sometimes they tend to traverse the rock in certain more or less definite directions. The richness of a stockwork is frequently increased by the impregnation of the rock itself.

General Remarks on Fissure-Veins.—From what has been said in preceding paragraphs, it will be gathered that a lode may present many different features throughout its course. It may be massive in some places, banded and brecciated elsewhere. It may widen and contract irregularly, and may even pinch-out again and again. At the same time it may be accompanied by parallel veins or lodes, some of which may be independent, while others may be off-shoots or branches, which, after continuing their courses for longer or shorter distances, may again converge and rejoin the parent lode; or, instead of doing so, they may gradually thin out either simply or by subdividing into a complex of veinlets and threads. Both walls may be well defined throughout; or one, usually the hanging-wall, may be rendered indistinct either owing to the multitudinous fissuring of the rock, or to the abundant dissemination of mineral matter through the pores and capillaries of the "country," or to the metasomatic replacement of the latter. Or dissemination and replacement together may succeed in obliterating both walls. On the other hand, many lodes are wonderfully regular, continuing between definite walls, showing much the same structure throughout, and varying but little in width or in the nature of their contents. Lastly, fissure-veins, instead of occurring as more or less well-defined lodes following some determinate direction, may form a close network of reticulating and intercrossing veinlets and threads, occupying all the cracks and crannies of a much divided and shattered rock-mass.

CHAPTER XVII

ORE-FORMATIONS—*continued*

Bedded Veins or Quasi-bedded Ore-Formations. Irregular Ore Formations—Masses occupying Cavities; Metasomatic Replacement; Impregnations; Disseminations; Contact Ore-Formations. Origin of Ore Deposits.

2. BEDDED VEINS OR QUASI-BEDDED ORE-FORMATIONS

WHEN sheets of ore occur apparently interbedded amongst more or less metamorphosed sedimentary rocks or schists, into which they send veins and threads, they may be termed bedded veins or quasi-bedded ore-formations. These formations are not to be confounded with the *flats* which are associated with "masses" (p. 258), and not infrequently also with lodes (p. 253), for they are not connected with true fissure-veins or lodes. Their origin is obscure. Not infrequently they seem to occupy planes of weakness or cavities, produced during the process of folding and metamorphism—for the rocks among which they occur usually dip at high angles and are more or less altered. The veinstone is commonly quartz which often carries gold and various metallic sulphides. While bedded veins of this kind are not infrequently of considerable width, and may simulate the persistence of true lodes, both as regards lateral and vertical extension, they are usually more or less lenticular and interrupted. A good example is furnished by the "saddle-reefs" of Bendigo Goldfield (Victoria, Australia) (see Fig. 112). The country-rock at this place consists of slaty shales and altered sandstones, disposed in a series of steep anticlines and synclines. The abrupt plication of the rocks has caused lenticular spaces to occur between adjoining beds in the cores of the anticlinal and synclinal folds. These spaces subsequently filled with quartz form the so-called "saddle-reefs." Each reef is thickest along the middle line or axis of a fold, the anticlinal reefs tapering off downwards and the synclinal reefs upwards. There would seem to be a succession of such reefs occurring one above another at greater or less intervals, the anticlinal reefs being more frequent and better developed than those occurring in the synclinal cores. At Bendigo, narrow dykes of dolerite are associated with the reefs. The reefs carry native gold and auriferous sulphides in small grains and particles, as well as sharply angular fragments of the country-rock.

It must not be supposed that the ore-formations here described as "bedded-veins" are always so sharply marked-off from the rocks amongst which they occur, as in the examples given. Often enough the ore-bed opens out, as it were, and so shades off gradually into overlying and underlying beds. In many cases, indeed, it is obvious that a so-called "bedded vein" or quasi-bedded ore-formation is merely a schistose rock, which has been so highly impregnated with ore that it can be advantageously mined.

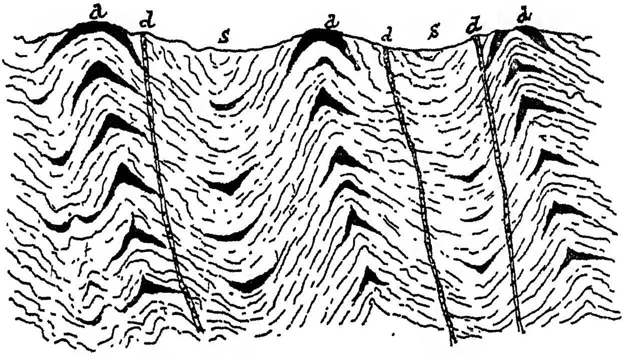


FIG. 112.—DIAGRAM-SECTION TO SHOW THE GENERAL STRUCTURE OF "SADDLE-REEFS."

a, *a*, anticlines; *s*, *s*, synclines; *d*, *d*, dykes.

It must be admitted that it is often very difficult to distinguish between such ore-bearing schists and those which have been described (see p. 238) under the head of syngenetic ore-formations. Probably not a few of the quasi-bedded ore-bodies associated with crystalline schistose rocks are largely of syngenetic origin—their original character having been more or less obscured by subsequent modifications brought about by epigenetic action. Amongst the quasi-bedded ores occurring in schists are both oxides and sulphides, but particularly the latter—such as zinc-blende, iron-pryite, chalcopyrite, galena, etc. The precise origin of many of these ore-bodies, as already remarked, is obscure. In some cases they may be the result of metasomatic action, and thus replace pre-existing beds. That many of the ores, however, are true impregnations and disseminations cannot be doubted. While the mineralisation may not infrequently have been effected during the period of metamorphism, it may sometimes have taken place at a later date.

3. Irregular Ore-Formations

1. **Masses.**—The ore-formations grouped under this head are met with chiefly in limestones. Sometimes they occupy underground cavities—the deserted courses of subterranean waters—which they partially or completely fill; in other cases the ore-formation would appear to be the result of metasomatic replacement—that is to say, the country-rock has been transformed into ore by the more or less complete chemical replacement of its original constituents.

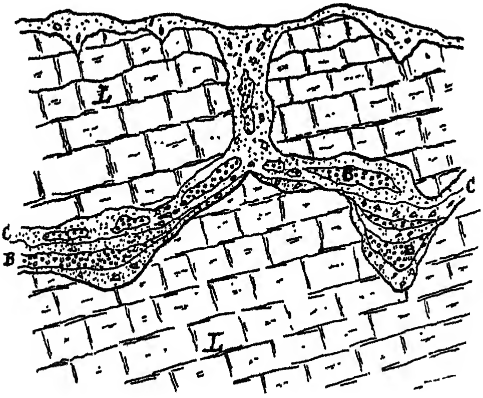


Fig. 113.—Diagram to show Mode of Occurrence of Bohnerz.

B, Bohnerz or oölitic limonite; *C*, cave-earth, etc.; *L*, limestone.

(*a*) *Masses occupying Cavities.* Among the best examples of this type are the Bohnerz deposits which are so frequently met with in the Mesozoic limestones of middle Europe (Fig. 113). Bohnerz is an oölitic or pisolitic limonite—the spherical grains of which vary in size from turnip seeds to hazel-nuts, and often show a concentric radiated structure. The ore is usually charged with many impurities such as clay, sand, etc., and not infrequently contains fossil organic remains of Tertiary age—such as mammalian teeth and bones, together with plants. In most cases the formation would seem to be a deposit from springs; but occasionally the ironstone occurs in the form of water-rolled fragments, associated with other sedimentary materials. It may be inferred, therefore, that these have probably been derived from some pre-existing formation, which has been broken up at the surface and the débris introduced underground by the mechanical action of water.

Irregularly shaped masses of hæmatite occurring in limestone may sometimes have been deposited in caverns and underground water-courses, and a similar origin has been assigned to many analogous masses of galena and zinc-blende enclosed in the limestones of various regions. The joints and even the bedding planes of a limestone, in the vicinity of a "mass," are frequently charged with the same ore, forming what are known as *flats*, *gash-veins*, *pockets*, *bunches*, *pipes*, *nests*, etc. (Fig. 114). It is very doubtful, however, whether the ore-masses in question occupy pre-existing cavities. Probably most of them should be included in the next group (*b*).

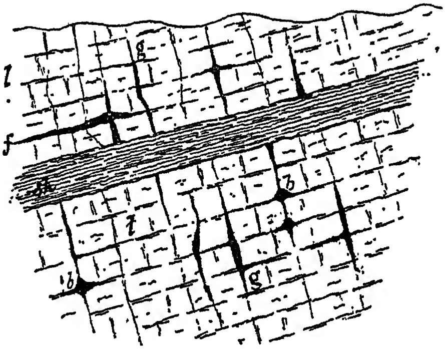


FIG. 114.—VEINS IN LIMESTONE.

l, limestone; *sh*, shales; *b*, *b*, bunches; *f*, flat; *g*, *g*, gash-veins.

(*b*) *Masses due to Metasomatic Replacement.* This remarkable change is well illustrated by the transformations undergone by limestone, which is sometimes replaced by ores of iron, lead, zinc, or silver. Some of the masses of red hæmatite met with in the Carboniferous limestone of Cumberland are clearly cases of metasomatic replacement, and possibly, as already suggested, the same is true of them all. The accompanying section (see Fig. 115), by J. D. Kendall, tells its own tale. Here the replacement of the limestone is rendered conspicuous by the shaly partings and layers which traverse the hæmatite, and are obviously continuous with the similar layers and partings in the limestone at b^1. The limestone has been transformed into ore, while the argillaceous shales (with which no chemical reaction could take place), remain unchanged. There is, moreover, a gradual transition from the hæmatite into the limestone—the one is not sharply marked off from the other. It may be added that the characteristic fossils of the limestone are often partly or completely changed into iron-ore. Similar phenomena occur in limestones and dolomites of various ages elsewhere. Thus, in Carinthia, Triassic calcareous rocks are metasomatically replaced by ores of lead and zinc, while in Nevada, Utah, and other regions in North America certain limestones have been extensively converted into silver-ores.

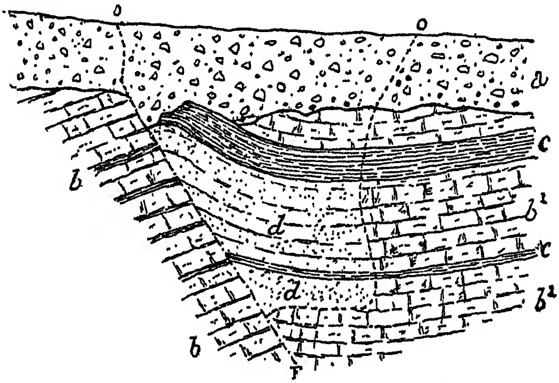


FIG. 115.—METASOMATIC REPLACEMENT OF LIMESTONE BY HÆMATITE.

a, boulder-clay; *b*, b^1, limestone; *c*, *c*, shales; *F*, fault; *d*, hæmatite replacing limestone; *o*, *o*, sides of the open cut. (After J. D. Kendall.)

2. **Impregnations.**—Reference has already been made to the impregnations which so frequently affect the walls of certain lodes and the rocks of a Stockwork. In cases of this kind the ores occur partly as disseminations (*i.e.* they occupy pre-existing pores and interstices), and partly as metasomatic replacements. For example, in a granite impregnated with tin ore we frequently find the ore not only occupying minute

fissures in the rock, but here and there replacing the feldspar, the form of which it retains. It is this constant passage of one type or form of epigenetic ore-formation into another that makes it impossible to separate them into well-defined or natural groups.

3. **Disseminations.**—Ores are sometimes disseminated through a rock in such a way as to show that they are not original constituents of the rock, but have been subsequently introduced; for they occupy its minute pores, interstices, capillaries, and larger cavities. A good example of this kind of ore-formation is supplied by the copper-bearing sandstones and conglomerate which were formerly worked at Alderley Edge and Mottram St Andrews, near Macclesfield. Green hydrated copper carbonate (malachite) and the blue variety (azurite) are disseminated through the cementing material of the rocks, the constituent grains and pebbles being in this way coated with ore. Small quantities of ores of lead, manganese, iron, and cobalt occur in the same sandstones. The auriferous conglomerates of the Rand in the Transvaal, S. Africa, have been cited by many authorities as notable examples of such disseminations. The strata of sandstone in which the gold-bearing conglomerates occur at Witwatersrand dip at a high angle (60° to 80°), but the inclination decreases as the beds are followed downwards. Gold occurs chiefly in the siliceous cementing material of the conglomerates, and is highly crystalline, appearing with sharp edges under the microscope. In this respect it differs from the gold of placers, much of which shows no trace of crystalline form. Associated with it are many secondary minerals, such as pyrite, marcasite, chlorite, talc, sericite, etc. The strata contain no fossils, but are known to be of pre-Devonian age. Their original deposition has been assigned by different investigators to marine, fluviatile and lacustrine agencies. Subsequently the whole series of deposits was subjected to crustal movement, being tilted, compressed, fractured, and faulted, and then or at a later period traversed by dyke-like intrusions of various igneous rocks (see Fig. 116). Concurrently with the crustal disturbance or with the igneous intrusions, siliceous and metalliferous solutions permeated the strata, making their way more readily through the conglomerates than the close-grained sandstones. Hence it is in the former that gold and crystallised minerals occur most abundantly. It is

worthy of note, however, that gold is confined to particular beds of conglomerate—other layers of the same kind of rock containing little or none. Possibly this may be explained by the presence of reducing agents in the one case and their absence in the other. According to Messrs Hatch and Corstorphine it is difficult to say what this reducing agent was. They point to the frequent association of gold with pyrite as suggesting that the latter had something to do with the precipitation; and they suspect that the carbonaceous matter—plentifully present in some richly auriferous portions of a conglomerate—may have played a greater rôle as a reducing agent than is commonly supposed.

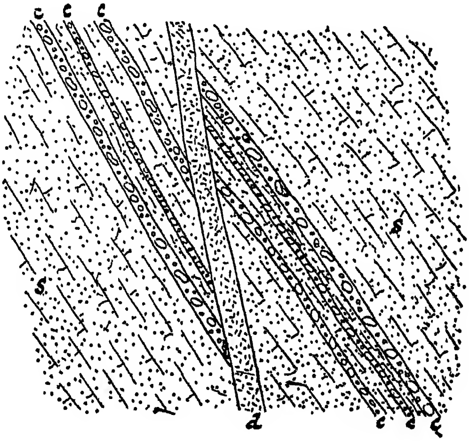


FIG. 116.—REVERSED FAULT IN THE GOLD-BEARING ROCKS AT JOHANNESBURG. (After Schmeisser.)

s, *s*, sandstones, etc.; *c*, *c*, *c*, beds of gold-bearing conglomerate (so-called " reefs "); *d*, dyke lying in fault.

It should be pointed out, however, that other authorities, and notably Professor R. B. Young in his work, *The Banket of the South African Goldfields*, regard these auriferous conglomerates as having been originally *Placers* in which the detrital gold has undergone subsequent solution and reprecipitation.

Yet another example of disseminations may be given. At Keeweenaw Point, Lake Superior, occur certain much decomposed igneous rocks (melaphyres) with interbedded conglomerates. Native copper is found both in the conglomerates and the igneous rocks, which are old lavas, the pebbles of the former being often encrusted with it, while the amygdaloidal cavities of the latter are frequently lined and occasionally completely filled with the same metal. Copper occurs also in the joints of the rocks and the fault-fissures traversing the strata, so that at Keeweenaw Point we meet with a union of at least two kinds of ore-formation—disseminations and true fissure-veins—both of which have doubtless had the same origin and were formed at the same time. The copper is often enclosed in, or itself encloses, zeolites, thus clearly showing it has been introduced as an aqueous solution. The whole series of rocks, after having been fissured and faulted, has been acted upon by hot and cold percolating waters, which have produced much alteration, probably leaching out the copper from the igneous rocks and depositing it where it is now found.

4. Contact Ore-Formations

Under this head are included sheets, irregular masses, ramifying veins and threads, etc., occurring in rocks usually at or near their junction with plutonic masses. These ore-formations include iron oxides and sulphides, and frequently also ores of copper, lead, zinc, tin, arsenic, antimony, mercury, etc.; and, in some cases, gold and silver. They may occur at or very close to the junction-line—particularly when the rocks surrounding the igneous mass are much broken and jumbled; or they may be met with at the surface for a mile or more away from an igneous batholith, but seem never to stray beyond the zone of altered and metamorphosed country-rock which surrounds it. They may occur in any kind of rock, and are frequently accompanied by the "contact minerals" referred to in a previous chapter (p. 221). Good examples are supplied by the cassiterite-veins which occur in genetic connection with batholiths of acid igneous rock, and the apatite-veins which are in like manner associated with masses of gabbro. The contents of these veins, as we have seen, appear to have been extracted from the still liquid or not yet fully congealed igneous masses and carried into the surrounding rocks. They are, in short, among the phenomena of contact metamorphism. According to Professor Vogt, who made such phenomena a special study, many other ore-formations met with in the vicinity of eruptive masses are of the same origin. He drew attention to the fact that the younger gold and silver veins (such as those occurring along the Carpathians, and at many places in Colorado, Utah, Nevada, California, Mexico, Peru, Bolivia, New Zealand, Japan) are in like manner closely associated with recent eruptions of igneous rock of various kinds. In each district where they occur they belong to the latest or one of the latest epochs of volcanic activity for that district. Hot springs, solfataras, etc., are frequently found near them, and even when these are absent the surrounding rocks are always more or less altered, as if they had been subjected to the action of heated water and vapours. The same authority would ascribe a similar origin to the older lead-silver veins of the Erzgebirge, the Harz, Kongsberg (Norway), Przibram (Bohemia), etc., and the old gold-quartz "Mother Lode" in California.

The ore-formations of Sarawak were shown by J. Somerville Geikie to be true contact-formations. They include ores of iron, antimony, arsenic, zinc, lead, mercury, etc., and native gold and arsenic. The region is occupied chiefly by Mesozoic limestone and shales, which are often highly shattered and brecciated and saturated with silica. Numerous dykes and sills of quartz-porphyry traverse these rocks, and are supposed to proceed from a concealed batholith of granite. Indeed, only a few miles away from the mines granite comes to the surface to form considerable hills. The ores occur not in the form of true lodes but mostly as impregnations and disseminations in the shales, and as irregular bodies in the limestone. Now and again the dykes yield a small percentage of gold.

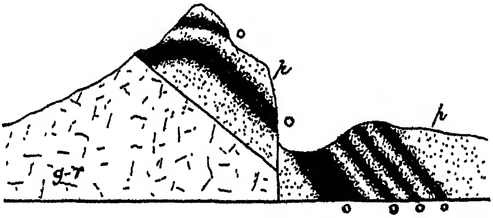


FIG. 117.—SECTION. CONTACT ORE-FORMATION OF GOROBLAGODAT (URAL MOUNTAINS). (After T. Tschernyscheff.)

g-r, garnet-rock; *p*, syenite and orthoclase-porphyry; *o*, magnetic iron-ore.

The magnetite deposits of Goroblagodat were formerly regarded as examples of segregations from a syenite magma, and such an origin is suggested by Tschernyscheff's section (see Fig. 117). More recently these ores have been claimed as contact-deposits, the magnetite being looked upon as replacing limestones.

THE ORIGIN OF ORE DEPOSITS

The primary origin of ore deposits is probably to be sought in the magma, or molten rock material, which, rising towards the surface, becomes emplaced at different levels in the earth's crust and forms the various types of intrusion (see Chapters XIII. and XIV.). Magma may be regarded as being made up of two sets of constituents:—(1) The *fixed constituents* which on cooling and crystallisation appear as the oxides, silicates, etc., of the eruptive rocks, and (2) the *fugitive constituents* which, on the crystallisation of the magma, are wholly or partly expelled and find their way into the surrounding rocks, where they proclaim their presence by the formation of certain characteristic minerals containing water, fluorine, chlorine, boron, sulphur, and phosphorus. While in the magma these constituents reduce its viscosity, lower the freezing point and aid differentiation; on the consolidation of the magma they pass out into the country-rock carrying with them in volatile or soluble form part of the metallic constituents which may be deposited as ores in fissures and cavities or in the form of irregular replacements or impregnations. There is commonly an association of certain ores with certain types of magma. Thus, ores of tin, tungsten, molybdenum, and iron occur usually along with acid rocks, while titanium, chromium, and platinum are most commonly associated with basic and ultra-basic rocks. Some of the ores tend to remain in the magma and form irregular masses intergrown with the rock-forming minerals, constituting *magmatic segregations*, which, however, are seldom of great value unless they are of large size or contain a valuable constituent like nickel, gold, or platinum. This may be called the *ortho-magmatic* phase of ore-formation.

Associated with many deep-seated intrusions are coarse-grained, dyke-like, and sill-like apophyses which are grouped in and around the parent intrusion, cutting it and the country-rock. These are known as *pegmatites*, and they are notable in that, though like the parent mass, they are more acid in composition and often carry rare minerals. In pegmatites associated with granites, crystals of magnetite, cassiterite, and wolframite may be found in small quantity. Occasionally it is possible to trace a pegmatite outward from the parent mass and to find that it passes gradually into a quartz vein carrying simple sulphides and gold, and such quartz veins, in view of their magmatic origin, have been called *vein dykes.* In addition to the pegmatites, and in the immediate neighbourhood of the intrusion, emanations from the magma may have filled fissures and cavities, effected replacement of limestones or impregnated masses of rock with ore and gangue. The foregoing may be regarded as representing the *pegmatitic* and *pneumatolytic* phase of ore deposition, so well illustrated by the occurrence and contents of the tin-bearing lodes of Cornwall.

Many ore deposits, though probably of magmatic origin, are so far removed from their source that the connection between them and their parent rock is not easily established. They commonly take the form of fissure fillings. The filling may be simple, indicating a single period of mineralisation, banded, indicating several injections, or brecciated, showing contemporaneous or subsequent movement of the walls. There are, however, indications of a definite sequence of ore depositions depending on depth or temperature. Thus, in Cornwall, it has been demonstrated that the lodes carrying tin near the parent granite carry copper in their higher levels. Elsewhere, it is suggested, a higher zone is marked by ores of lead and zinc, while still higher and nearer the surface may occur compounds of antimony and mercury. These different levels are considered to be *primary depth zones* of ore deposition. As the contents of the lodes referred to here have been transported in the form of hot solutions from a magmatic source they may be taken to represent the *hydrothermal* phase of ore formation. It must be noted, however, that many lodes show no connection with eruptive rocks, and their formation by the action of underground water, heated by penetration to deeper levels, cannot be excluded.

While the eruptive rocks afford evidence of the way in which ores may be brought within reach of the surface, very many important ore deposits are clearly *secondary,* and represent modifications of primary deposits by the action of underground water and surface weathering. With certain ores, notably those of copper, the secondary changes brought about in this way are important. By the leaching of the copper above the water table and its redeposition at, or just below, that level the primary deposit may be locally enriched. If iron is present, as it usually is, the outcrop of the lode is marked by a red or brown vesicular *gossan,* beneath which comes the *zone of oxidation,* leading to the *zone of secondary enrichment* near the water table and to the zone of primary ore below. Other secondary ores have been produced by the leaching by ground water of metallic compounds disseminated through a great mass of rock and its deposition underground along channels or by replacement of other more soluble rocks. Such appears to have been the mode of formation of the iron ores of Cumberland by leaching of the iron in the desert beds of the New Red Sandstone rocks and its deposition, mainly by replacement, in the underlying Carboniferous Limestone.

Very important ores, especially of iron, have been formed by ordinary processes of sedimentation, the ore being in part of detrital origin but mainly deposited from solution. The bog and lake iron ores of freshwater swamps and lakes, the clay-band and black-band ironstone of the Carboniferous rocks and the mixed carbonate and green silicate ores of Jurassic age in England are good examples.

Other secondary ore deposits appear as land-surface residues, the accompanying rock having been wholly or partly removed in solution. Special climatic conditions and long protection from active erosion are necessary for the formation of this type, which is well exemplified by the usual occurrence of the aluminium ore, bauxite, and certain important ores of manganese.

Superficial secondary deposits may take the form of ore-bearing sands and gravels which represent the weathered residues of a land-surface transported by the wind, by running water or the waves of lakes or seas, and sorted and redeposited according to size and specific gravity. Only minerals highly resistant to chemical and mechanical action can occur in such deposits, which are well illustrated by the familiar gold placers and platinum- and tin-bearing gravels.

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CHAPTER XVIII

GEOLOGICAL SURVEYING

Geological Surveying. Field Equipment. Topographical Maps. Data to be Mapped. Various Scales of Maps. Signs and Symbols. Tracing of Exposed Outcrops. Tracing of Concealed Outcrops—Evidence supplied by Soils and Subsoils, by Vegetation, by Form of Surface, by Springs, by Index-beds, by Alluvial Detritus. Carrying Outcrops across Superficial Formations.

IT is quite possible to acquire a considerable knowledge of Geology by the mere intelligent perusal of text-books. Without having engaged in practical work, one may even learn to read a geological map, and come to understand in a general way the structure of the region it portrays. Knowledge obtained after this fashion, however, is necessarily superficial, and can never supply the place of personal observation or study in the field. It is only after the student has familiarised himself with the phenomena themselves, that the full meaning of what he may have read about them will dawn upon him. The best counsel, therefore, which one can give a beginner is to commence observation in the field at the earliest opportunity, even before he has gained more than a mere elementary acquaintance with the stony science. Some preliminary knowledge of common minerals and rocks is doubtless desirable, and the student will be all the better prepared for his field-work should he have learned to recognise some, at least, of the more important type-fossils of the several geological systems. Such elementary knowledge, however, is not hard to acquire, and the want of it need not deter him from beginning the study of rock-structure. A profound acquaintance with this important branch of geology has been obtained by several noted observers, who could hardly be said to have had much preliminary training in either mineralogy, petrography, or palæontology.

The best method of getting a grasp of structural or tectonic geology is to attempt the construction of a geological map from one's own observations. There are few more engrossing or interesting pursuits than that of unravelling geological structure, and the investigator will find that the labour involved is amply repaid. For not only does he gain a precise and intimate knowledge of the country surveyed, but he learns to appreciate geological processes and their results as he cannot do in any other way. His conceptions of what is meant by denudation and the origin of surface features; of crustal disturbances large and small; of the metamorphism of rocks, and a thousand other questions will be broad and assured, or narrow and uncertain, according as his knowledge has been derived at first hand from his own personal observation or at second hand from books.

Our first attempts at mapping will likely enough be halting and unsatisfactory, but, with zeal and patient endeavour, experience and success will follow. After having devoted due attention to the subject, we may expect in time to acquire such facility in reading and interpreting the stony record, that only one or two rapid traverses of a region may suffice in many cases to disclose to us its geological structure. Indeed, the mere configuration of the ground will often reveal to a trained observer the leading geological features of a country, and enable him to produce a reliable sketch-map. Experts, however, are not infallible, and in rapidly traversing a region may miss important evidence which could not have escaped them had the ground been carefully surveyed.

Field Equipment.—The apparatus required in geological mapping is fortunately neither elaborate nor heavy. There are field-geologists who in some way or other manage to conceal about them all that is essential for the purpose. Others, again, are so elaborately accoutred as to attract the attention of every passer-by. The only necessary apparatus, however, consists of the following:—a hammer, a pocket-lens, a compass and clinometer, a note-book, a fountain-pen, a common lead-pencil, and a good, reliable topographical map. To these it is well to add a small protected bottle of dilute hydrochloric acid, and, of course, a pocket-knife.

The Hammer. In the selection of a hammer tastes differ. For general purposes, however, that used by the officers of the Geological Survey can hardly be surpassed.* It should not weigh much over one pound—unless the observer expects to be working principally among hard and tough rocks, such as granite, gneiss, and schists, when it may be desirable to have a somewhat heavier implement. The student will soon learn, however, that there is a certain art even in breaking stones. An adept by one dextrous blow with a light hammer will often strike off a "specimen" from some hard, tough rock, which a tyro armed with a much heavier tool may vainly assail—all his efforts resulting only in the production of so much grit and powder. There is some art not only in the elastic swing of the arm as the blow is delivered, but in the selection of the spot to be struck, which will be determined partly by the shape of the rock-surface and partly by the nature of the rock itself.

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* This hammer is introduced into many of the Plates illustrating this book; see especially Plates XXXII., XXXIX., LI., LIV., LV.

If the geologist wishes to collect rock-specimens as he goes along, a heavier hammer will be necessary to detach fragments of a sufficient size, besides which a much smaller tool will be required to trim the specimens to the desired size and shape. To these some geologists add one or more chisels, such as are used by masons. These additional impedimenta may be carried in the strong canvas bag required to hold his rock-specimens and fossils. Heavily burdened in this way, however, the progress of the hammerer is apt to be impeded; and if his chief object be mapping, he will do well to leave specimen-collecting alone until his survey is completed. After his map is finished, he can devote a few days to gathering such specimens as he wishes to procure. As geological surveying often involves climbing in ticklish places, and much hard walking over rough ground, it is well to go as lightly as one can, if rapid progress be desired. A few capacious pockets to hold the small specimens and chips one may wish to examine carefully at home will be found more convenient than a bag—the temptation to fill which with choice but weighty material is often too great to be resisted.

The Lens. This is an important adjunct, and is so easily carried that no field-geologist should be without it. Even the best eyesight may fail to diagnose the finer grained rocks, but there are few of these the character of which cannot be determined by means of a lens. For ordinary purposes the lens need not be of very high magnifying power; it is well to select one giving a flat field and good depth of focus.

The Compass. This instrument is primarily used to determine the direction in which strata are inclined, and for this purpose any pocket compass will serve. It is often very desirable, however, to take bearings in order to fix the trend of some dyke, fault, or other structure, or to determine the exact position where some observation is made. This is readily done by means of a prismatic compass. An instrument of this kind, however, is seldom required by the student who is provided with an accurate large scale map, such as the 6-inch map of the Ordnance Survey.

The Clinometer. With this instrument the angle of dip is measured in the manner already described (p. 127).

The beginner will probably find it most convenient to use an instrument in which compass and clinometer are combined. Being the size of an ordinary watch it slips easily into the waistcoat pocket.* The chief drawback to this instrument is that the edge which is to be held parallel to the line of dip is too short. The edge may be "lengthened," however, by placing it on the note-book, the hammer-handle, or the walking-stick—if the geologist feels it necessary to burden himself with one. He will find ere long that a stick is rather a hindrance than a help, and will probably succeed in losing it before his first day's work is done.

The Note-Book. This should not be too small nor yet too large to slip into a side-pocket. A convenient size is 6 inches by 4 inches—for the book when opened can then be used as a rough-and-ready foot-rule for measuring purposes. The paper may be plain or ruled according to taste. As the book is meant, however, to contain not only notes and descriptions but sketches of geological sections, it is advisable to have some of the paper ruled into squares. These squares may represent inches, feet, or yards, and thus enable the observer to sketch on a correct scale any rock exposure which can be conveniently measured. Until some facility in drawing has been attained, it is best to use first a common lead-pencil, and afterwards to ink-in the lines. With practice, however, the observer may eventually be able to discard the pencil and to sketch directly with his pen. For clearness sake it is often advisable to colour a section. Coloured pencils may serve for this purpose, but in a note-book such colours are apt to get rubbed and smudged, and ordinary water-colours, therefore, are preferable. Those who have an artistic aptitude enjoy a great advantage, and can often do without the help of square-ruling—bringing out with a few deftly drawn lines on plain paper all the geological features that call for expression. They can fill their note-books also with sketches of scenery which may show at a glance how the configuration of the ground has been determined by the nature and structure of the rocks. If the observer has this gift, he would do well to cultivate it—for he may be sure that his descriptions of geological phenomena will gain enormously in clearness and value when they are accompanied by well-selected artistic illustrations.

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* A very serviceable instrument of this kind is supplied by Messrs Cooke, Troughton & Simms, Ltd., Kingsway North, York. See Appendix C.

To others who have not been blessed with artistic talent, photography lends much assistance, and is therefore largely indulged in by field-observers—good portable cameras being readily obtainable.

The Topographical Map. Reliable topographical maps of most civilised countries can now be obtained. In our islands the maps issued by the Ordnance Survey cannot be surpassed for accuracy, and are just such as are desiderated by the geologist. These maps are on various scales—those on the scale of 6 inches and 1 inch to the mile respectively being most useful for geological purposes. The beginner will find the larger scale map the more satisfactory of the two, as it enables him to plot his observations in much greater detail than would be possible on the other. The shape of the ground is indicated by numerous contour lines (*i.e.* lines of equal elevation) instead of by "hill-shading," so that pencilled notes and lines are clearly seen, and the observer is usually saved the trouble of determining heights which, for various geological purposes, it is often necessary to ascertain.

When large maps like those referred to are not available, and the observer has to content himself with maps on a much smaller scale, he may occasionally be compelled to redraw portions of his map on a larger scale. Such will be the case when the geological structures are so highly complicated that they cannot be indicated save in a generalised way on a small map. Every field geologist's note-book is sure to contain enlarged sketch-maps of this kind, showing in detail complex structures which it would be impossible to represent upon any ordinary topographical map. And such enlarged portions of his map may serve subsequently as illustrations to accompany the observer's monograph or paper descriptive of the region surveyed.

The maps of some countries which are only sparsely settled are often little better than generalised sketches, making no pretensions to accuracy; while the topography of many wide regions has not yet been delineated even in outline. Geologists in such cases must be prepared to do some topographical surveying for themselves if they wish to prepare a geological map. In several of our colonies surveying of this kind has been carried on by geologists concurrently with their own special work. Students of geology, therefore, if they intend emigrating, should certainly acquire some knowledge of topographical surveying before leaving home. Even if they have relatively accurate maps provided for them, they may yet frequently find it necessary to correct these or to lay down the topography in greater detail.

Geological Data to be Mapped.—Assuming that the student begins his field work in this country, he has, of course, accurate and detailed maps at his service, which is a very great advantage: for it will readily be understood that when the topography is inaccurate the geological lines cannot be otherwise than distorted. An approximately perfect geological map must, therefore, in the first place, be thoroughly accurate as regards its topography. It should also be on not too small a scale, for the larger the map the greater the detail that can be shown, and the more readily and exactly are geological positions determined. To be of any practical use, a good geological map ought to exhibit the following features, viz.:—

(*a*) The superficial areas occupied by geological systems and their chief subdivisions—the mutual boundaries of the several groups or series being accurately delineated.

(*b*) Individual seams, beds, or formations of economic or scientific interest and importance, such as coals, limestones, ironstones, etc., the position of available building-stones, etc.; the best sources of underground water-supply; the general character and distribution of superficial accumulations, subsoils, and soils.

(*c*) Igneous rocks—effusive being clearly distinguished from intrusive rocks.

(*d*) Faults, and all fissures which may be supposed likely to contain ore-formations.

(*e*) Dips should be everywhere carefully inserted, so as to show exactly the direction and degree of inclination of the strata.

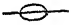
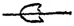
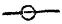
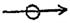
A map containing these data would enable a geologist, who might never have visited the region represented, to understand at a glance the geological structure. From the details given, he could measure the thickness of the strata and ascertain the depths from the surface at which particular seams or beds might be expected to occur at given points. He would be in a position to indicate where an underground water-supply might be tapped by borings—all this, and much more, a carefully constructed geological map will reveal to anyone who has the skill to read it. Only large scale maps, such as those issued by the Geological Survey of Great Britain, are sufficiently detailed to be used in this way. The field-observations of the Survey are plotted on the larger Ordnance Map (6 inches to a mile), and the sheets representing the more important parts of the country are published on that scale. The several geological systems and their subdivisions, and the general structure of a region, however, can be quite well represented on a smaller scale. The Geological Survey, for instance, issues a general map, on the scale of 1 inch to a mile, the information given on which is, of course, taken from the larger map. Having been carefully reduced from the 6-inch field-maps, the smaller map is sufficiently accurate and detailed for general purposes.

The maps issued by national geological surveys are seldom on a larger scale than 1 inch to a mile, and are usually much smaller. Such maps do little more than represent the broader geological features, the distribution of the several systems and their larger subdivisions, together with the more important developments of igneous rocks, leading lines of dislocation, position of ore-deposits, etc. They are accompanied, however, by more or less elaborate monographs, which contain such detailed information as could not be expressed upon the maps themselves. And the geology of the regions represented on the latter is still further explained by means of horizontal (or profile) and vertical sections, the former being constructed so as to indicate or represent the shape of the surface and the geological

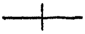
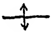
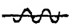
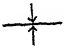
PLATE LX

SIGNS USED ON MAPS OF H.M. GEOLOGICAL SURVEY

Signs connected with the Glacial Drift

	Roches moutonnées (not striated).
	Roches moutonnées (striated), but direction of ice-flow not apparent.
	Roches moutonnées (striated), showing direction of ice-flow.
	Plane or flat surface (striated).
	Plane or flat surface (striated), where direction of ice-flow is visible.

Signs connected with Stratification

	Horizontal			Steeply Inclined Strata.
	Vertical (longest line the strike)	Beds.		Cleavage.
				Anticlinal Axis.
	Contorted			General Dip of Undulating Beds.
	Inclined Strata.			Undulating Strata.
	Gently Inclined Strata.			Synclinal Axis.

Interrupted Lines — — — — — show a doubtful or drift-covered Boundary.

White Lines, Faults.

Signs indicating the Ores of the Metals

☉	Gold.		Manganese.	♃	Tin.
♄	Lead.	♀	Copper.		Zinc.
☽	Silver.	♂	Iron.	⊕	Nickel.

Gold Lines, Mineral Veins.

structure of the ground, while the latter are designed to show in as great detail as possible the succession of important groups or series of strata, such as coal- or ironstone-bearing formations. (The method of constructing geological sections is set forth in Chapter XXI.)

Small generalised geological maps, on a scale of 10 miles to an inch or less, are designed to show merely the distribution of the chief rock-divisions, and have usually been reduced from larger maps. Sometimes, however, outline- or sketch-maps of this kind are original productions, accompanying the descriptions of hitherto unknown or imperfectly known regions. They are meant to do no more than illustrate the pioneer work of geological explorers, and do not therefore make any pretension to minute accuracy.

To the student who would become an expert field-geologist, topographical maps on a scale of less than 1 inch to a mile are of little use. Even a 1-inch map cannot be recommended to one who has all his experience to gain. The beginner who has the good fortune to commence work in this country cannot do better than follow the example of our Geological Survey and use the 6-inch Ordnance Map. Although this map is large enough to allow here and there of notes being inserted, the observer will soon find it necessary to use abbreviations, signs, and symbols. For example, instead of writing *sandstones and shales*, *SS* or *Sa & Sh* will suffice. In like manner, most of the common igneous rocks can be indicated by means of the initial letters, as *B* for basalt, *G* for granite, *Sy* for syenite, *D* for dolerite, *Di* for diorite, *A* for andesite, and so on. Plate LX. shows some of the signs and symbols used by the Geological Survey of Great Britain and Ireland.

Tracing Exposed Outcrops.—As the most continuous exposures of rock naturally occur upon sea-coasts and along river-courses, it is best for practice to select, if possible, some tract the situation and topography of which seem to promise the observer most information. Proceeding along the sea-coast, and following the stream-courses of a region which we shall suppose consists largely of stratified rocks, the student must insert upon his map the direction and angle of dip as frequently as possible. The outcrops of all notable or important beds and seams (such as limestones, coals, iron-stones, etc.) are carefully set down, and particular descriptions of these and the accompanying strata are recorded in the note-book. Fossils are sedulously searched for everywhere, more particularly in the finer grained argillaceous sandstones and shales amongst which seams of coal and ironstone or beds of limestone not infrequently occur. Should any seam or layer be characterised by the presence of certain fossils peculiar to itself, the exact position of such seam should be carefully indicated, for it may be of great service as a datum-line or geological horizon, as will be shown presently. Bedded ironstones and limestones are often marked by the presence of special fossil-forms, and this is one reason why the outcrops of such rocks are invariably mapped by a field-geologist. Any stratum or series of strata, however, which may be notable on account of fossils or lithological character, must be distinguished from immediately overlying and underlying strata. Not infrequently it is possible to separate a great succession of sedimentary deposits into subordinate groups—each, it may be, marked by the presence of particular fossils, or by the composition and structure of the rocks themselves.

Tracing Concealed Outcrops.—After the observer has examined every exposure of rock upon the sea-coast, in river-courses, and elsewhere, and exhausted all the evidence to be obtained in railway-cuttings, quarries, and other excavations, he will usually find that there are wide areas over which no rock appears at the surface. The surface may be concealed under thick soils and subsoils, or overspread by superficial accumulations of various kinds, as clay, sand, gravel, peat, etc. How are such blanks in the evidence to be filled in? How can we carry the lines of outcrops across tracts which are apparently so hopelessly mantled? Fortunately, it is usually possible to follow lines of outcrop even when the rocks themselves are not actually seen, for, although concealed, their presence is often betrayed in various ways. The following are some of the sources of information of which a keen-eyed observer will avail himself:—

(a) *Soils and Subsoils.* In regions which are not covered by glacial deposits (such as boulder-clay), or by thick sheets of transported materials (sand, gravel, etc.), the soils will usually indicate the nature of the underlying solid rocks, fragments of which are almost certain to occur more or less abundantly. These will, of course, be readily detected in newly ploughed ground, but when the soil is carpeted with vegetation, information is nevertheless often obtainable from worm-castings, mole-heaps, rabbit-burrows, etc. A red, sandy soil, containing angular fragments of red sandstone will indicate the presence of red sandstone underneath. Tenacious clay-soils, with few or no stones, will be found to pass downwards into marls, clays, or argillaceous shales. Should subangular, blunted stones (some of them, perhaps, striated) occur numerously in a stiff clay soil, the presence of till or boulder-clay is indicated. A soil charged with numerous rounded water-worn stones will be found to overlie either a superficial deposit of gravel or a decomposing conglomerate.

In estimating the value of the evidence furnished by surface stones, it is well to remember that if the stones, whether subangular or rounded, should consist of many different kinds of rock, they must be derived from an underlying superficial accumulation of transported materials, or, as just remarked, they may indicate the presence below of a disintegrating conglomerate, the outcrop of which the observer will probably have already encountered in some natural or artificial exposure—say, in sea-cliff, river-course, or railway-cutting. Although a soil be charged with abundant angular fragments of one and the same kind of rock, it does not necessarily follow that the parent rock from which these fragments have been derived will be encountered immediately underneath the surface. Much will depend upon the configuration or shape of the ground. All soils and disintegrated rock-materials tend to travel downwards from higher to lower levels, and, in this way, soil derived from one kind of rock comes to overlap and to be commingled with soil derived, it may be, from quite a different class of rock-material. The annexed diagram (see Fig. 118) will serve to illustrate this point. Here there are three separate beds represented—*a* being a dark red marl; *b*, a grey sandstone; and *c*, a coarse conglomerate. The soil overlying *a*, which occupies the top of the hill or bank, is red and argillaceous, and as this soil tends to travel down the slope it invades the outcrop of the stratum *b*, where it becomes commingled with grey sand, derived from the disintegration of the sandstone. There is thus a gradual passage from a pronounced dark red clay soil into a more or less arenaceous soil of a lighter tint—the red colour gradually becoming less and less conspicuous as the base of the slope is approached. It is obvious that angular fragments of grey sandstone may be met with in the soil, at all levels from the outcrop of *b* downwards, while stones from the conglomerate will be confined to the soil that overlies that stratum. This commingling of soil and disintegrated rock-débris along the boundaries of formations is everywhere observable, and the geologist, therefore, in drawing his boundary-lines, must make the necessary allowances. In the case represented in the diagram there would be no difficulty in ascertaining the boundary-lines between the several beds. Walking up the slope the presence of rounded stones would indicate the presence of the conglomerate, so long as even one or two only appeared. Above the junction of beds *c* and *b* water-worn stones would no longer be met with, while fragments of sandstone might continue to abound until the limits of the stratum *b* were nearly reached. The position of the boundary-lines to be drawn would thus be approximately indicated.

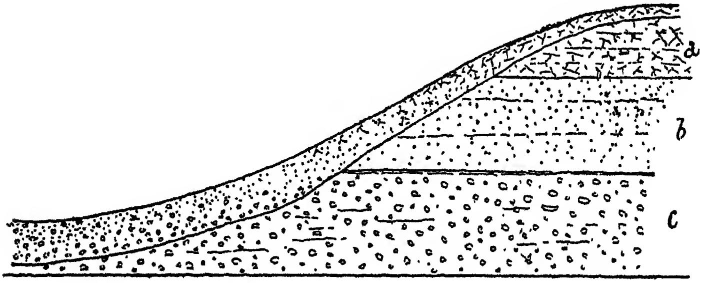


FIG. 118.—TRAVELLING OF SOIL AND SUBSOIL.

Although the colours of soils are invariably due to the character of the rocks from which they have been derived, the observer must remember that the colour of unweathered rocks often differs greatly from that of their disintegrated débris. The brown and reddish colours of many soils are due to the presence of iron-oxides, but such soils are often derived from rocks which are neither brown nor red—these colours having resulted from the chemical alteration of the rocks. Many basic igneous rocks, for example, which may be dark blue or even black, yield yellowish and reddish-brown soils. Again, some kinds of blue and grey boulder-clay are overlaid with reddish-yellow soils. Many impure blue and grey limestones also tend to yield yellowish or brownish soils.

Generally speaking, however, the colour of soils formed from the disintegration of derivative rocks does not, for obvious reasons, differ much from that of the rocks themselves.

(*b*) *Character of Vegetation.* The character of the vegetation is often an index to the nature of the soil and underlying rocks which the observer cannot always afford to neglect. It is well known that certain plants prefer one kind of soil to another, so that botanists are able to map out a region into areas (not always, it is true, sharply defined), each of which is distinguished by the development of some particular assemblage of plants, or by the presence of certain plants and the absence of others. As the distribution of these plant-societies depends mostly on the chemical and physical conditions of the soil, it is necessarily suggestive to the geological observer. Soils poor in carbonate of lime show a different assemblage of plants from those which are rich in that substance. There are certain species (*e.g.* common bracken, common heather, sorrel, fox-glove, etc.) which avoid calcareous soils; while, on the other hand, not a few species (*e.g.* wild cherry, beech, dogwood, and many flowering plants) are particularly partial to such soils. Porous sandy soils, tenacious clay, loose loams, saline soils, etc., are each characterised by the presence of distinctive plant-groups. In the absence of rock-exposure, therefore, the plant-associations referred to may often be helpful to the field-geologist, and enable him to draw his boundary-lines with more or less confidence. He must bear in mind, however, that the boundary-lines suggested by the varying character of the vegetation will not often coincide even approximately with the junction-line he is in search of. Soils, we have seen, tend to travel down slopes, however gentle these may be, and in this way a soil rich in lime may eventually come to overlie a quartzose sandstone which might contain hardly a trace of lime; just as, on the other hand, a barren, infertile sand may in time invade and cover rocks, which, if left exposed to the weather, would naturally have yielded a highly fertile soil.

Nevertheless the observer, who has a sufficient knowledge of botany, will not infrequently have occasion to turn this knowledge to good account. Having ascertained the character of the flora which he finds growing upon soils in places where their derivation from the underlying rocks can be seen, as it were, taking place, the appearance of a like plant-assemblage elsewhere will lead him to suspect the presence of the same rocks below, although none of these may be actually visible at the surface.

(c) *Form of Surface.* The shape or configuration of the ground is frequently of great service in showing where a boundary-line should be drawn. As will be set forth more fully in the sequel, the forms assumed by a land-surface are determined in chief measure by the nature of the underlying rocks and their geological structure. Rocks differ greatly as regards durability—some being much more readily reduced than others by the superficial agents of change. Hence, in regions which have been long exposed to denudation, the less readily disintegrated rocks tend to project, while the more yielding kinds are correspondingly worn-down or levelled. It is a matter of common knowledge, indeed, that hills and ridges are usually, or at least very often, built up of relatively harder or more resistant rocks than those that occupy contiguous, low-lying tracts. This, however, is not invariably the case, as will be shown later on. Not infrequently the hills of a country consist of no harder or less readily disintegrated rocks than are found in the low grounds. In a great many cases this is due to the geological structure or arrangement of the rocks. There are certain structures that tend to resist while others favour denudation. Hence a series of strata, having the same consistency throughout, may in some places form hills, while elsewhere they may occupy depressions of the surface. In the above diagram (see Fig. 119), for example, it is obvious that the position of the hills has been determined by the strong synclinal arrangement, while the weaker anticlinal structures have been more readily reduced. If the observer be geologising in a region where the rocks are inclined for long distances in the same direction, he will usually find that the outcrops of relatively harder beds tend to project more than those of the less durable strata amongst

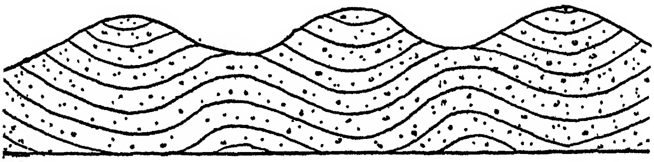


FIG. 119.—SURFACE-FEATURES IN GENTLY-FOLDED SANDSTONES.

which they are intercalated. Hence, even when the naked rock is concealed by vegetation and soil, it nevertheless will form a feature. Thus, in the accompanying section (Fig. 120), we have a series of limestones and shales, the outcrops of which are not actually seen, and yet their position is indicated by the form of the ground. It is obvious, indeed, that the occurrence of a thick bed of relatively hard rock intercalated in a series of softer or more yielding strata, inclined in one and the same direction, must, under the influence of denudation, give rise to the formation of escarpments or ridges—which, whether the naked rock be actually exposed or not, will form prominent features in a landscape. In the case of countries which are built up of horizontal strata, the varying hardness of the rocks will similarly affect the form of the ground, and cause it to assume a terraced aspect—a structure illustrated in the same diagram (Fig. 120), where the gentler slopes correspond with the outcrops of " soft " rocks, and the more abrupt gradients with the outcrops of " hard " rocks.

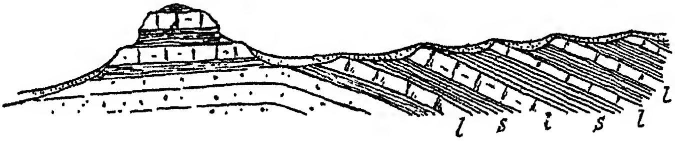


FIG. 120.—FORM OF GROUND INFLUENCED BY GEOLOGICAL STRUCTURE.

It must be borne in mind, however, that in countries heavily covered with glacial and other superficial accumulations, the surface configuration of the underlying solid rocks is often obscured or even entirely concealed. But when such deposits are either absent or attain no great thickness, the form of the ground is always of the greatest assistance to the geologist who is trying to carry a line of outcrops across a country.

(d) *Springs.* Considerable aid in tracing boundary-lines is sometimes afforded by springs. When layers of relatively impervious materials, such as shales, clay, etc., are intercalated among a series of porous strata, underground water tends to come to the surface along the line of junction between the porous and the non-porous strata. This will often happen when bedded rocks are truncated by the slope of the ground, the water appearing in the form of springs or oozing out slowly and giving rise to marshy and damp spots. Should a number of such springs or seepage-places occur in succession in some given direction, they will necessarily indicate the presence of a geological boundary-line. Occasionally spring-water is highly charged with mineral matter, such as carbonate of lime, iron-oxide, etc., and hence deposits of calc-sinter, bog-iron ore, etc., tend to be formed at the surface along the junction between porous and impermeable strata. (For a more particular account of springs, see Chapter XXIII.)

(e) *Index-beds.* Although it is true that the most continuous exposures of rock are to be met with along the seashore and in river-valleys, it nevertheless often happens that, owing to the presence of superficial accumulations, the rocks in a valley may be concealed for longer or shorter distances. But should the observer have previously examined the strata over a considerable area, the occurrence of such blanks in the evidence does not necessarily disconcert him. He probably recognises, in the few sections available for study in some particular valley, portions of a series of beds, the stratigraphical position of which has already been revealed by more continuous sections exposed elsewhere in the same district. After he has carefully studied the strata of a wide area, he will frequently find that a great thickness of strata may show a monotonous alternation of the same kinds of rock, say, sandstones and shales, and yet these may exhibit sufficient variety of lithological character to allow of the whole series being roughly divided. Perhaps thick-bedded coarse-grained sandstones and grits with subordinate shales may prevail at one horizon, and shales with occasional thin beds of fine-grained sandstones may predominate elsewhere. Possibly, also, the shales at stated intervals may contain nodules of a particular kind, or there may occur at a definite horizon some stratum characterised either by its fossils or by certain peculiarities of composition, texture, or structure. Beds of this kind are not infrequently persistent over considerable areas, and when such is the case they are invaluable to the field-geologist. They may not be of sufficient importance to be mapped separately from the series in which they occur, but their presence in a section at once indicates the stratigraphical horizon. Should the observer have ascertained that an "index-bed" of this nature lies at a given distance above or below any limestone, coal, or other valuable seam he may be desirous of mapping, it is obvious that the appearance of the index-bed in a valley must enable him to fix the approximate position of the seam he is in quest of—no matter how deeply the outcrop of the latter may be buried under alluvium. The field-geologist, therefore, cannot be too careful in acquiring a full knowledge, not only of the particular beds whose outcrops he seeks to trace, but of the varying characters of the several groups or series of strata with which those beds are interstratified. An adequate detailed acquaintance with the whole series of rocks occurring in a district often enables the observer to locate the geological horizon of isolated rock-exposures, and to plot the position of boundary-lines with wonderful accuracy, even in places where the ground is thickly mantled with superficial deposits.

(f) *Transported Detritus in Stream-courses.* In cases where the geological position of the rocks exposed in a stream is not suggested by the character of the rocks themselves, the field-geologist does well to examine carefully the gravel and detritus, as he proceeds up the valley. Should he detect fragments of a rock, say, limestone, which he has already encountered *in situ* elsewhere in the same district, he makes careful note of his find and continues to follow the spoor up-stream. Possibly the limestone fragments become more and more numerous as he goes on his way, while, at the same time, they are less water-worn and occasionally perhaps attain a relatively large size. Eventually, at some particular spot they cease to occur—the obvious inference from which is that the limestone itself must crop out here or at some short distance up-stream. In a case of this kind a geologist would naturally seek to strengthen the evidence by carefully examining the adjacent valley-slopes for similar angular fragments.

After direct and indirect evidence of every kind has been exhausted, we probably find that there are still certain spaces upon our map across which boundary-lines cannot be traced. Wide sheets of peat or alluvium, for example, may effectually conceal broad areas. Should the map we are using be on a large scale, say 6 inches to the mile, we should stop the lines abruptly where they meet the obscuring sheet of alluvium or peat, and colour the latter as a separate formation. On small-scale maps, however, it may be desirable in many cases to carry a line—more especially if it be the outcrop of some important or valuable seam—across areas which are covered by peat or alluvium. This may be safely done when we have assured ourselves that there is no interruption or break in the continuity of the strata. When the conditions are such as represented in Fig. 121, there can be no doubt that the outcrop of the limestone (*a*) must continue across the area concealed by the peat (*x*), seeing that the outcrop of the upper limestone (*b*) has been followed without interruption from west to east, while there is clear evidence of a continuous succession of strata between *a* and *b*.

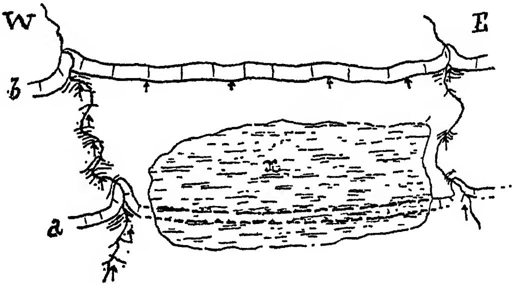


Fig. 121.—Concealed Outcrops.

In all cases, however, where an outcrop is inferred from indirect evidence, a conscientious and cautious observer will be careful to indicate this by drawing dotted or interrupted instead of continuous lines. Continuous lines should mean that the outcrops are actually visible—that the rock can be seen *in situ*; while interrupted lines should merely indicate the position at or near which the observer thinks it likely that the outcrop may be found.

CHAPTER XIX

GEOLOGICAL SURVEYING—*continued*

Forms of Outcrop. Measurement of Thickness of Strata. Thickening and Thinning of Strata. Unconformity. Overlap. Normal Faults. Reversed Faults. Eruptive Rocks and Contact Metamorphism. Regional Metamorphism.

Forms of Outcrop.—The form and direction of an outcrop naturally vary with the configuration of the ground and the direction and angle of dip. As a rule, the most winding and sinuous outcrops appear among horizontal strata, especially when these have been deeply trenched and eroded. Gently inclined strata also frequently yield very sinuous outcrops, while the outcrops of steeply inclined or vertical beds are usually more regular in their trend, and sometimes run for long distances in approximately straight lines.

Horizontal Strata. In the case of an undulating plateau built up of horizontal strata, and traversed in different directions by many valleys, the outcrops necessarily follow all the windings of the latter—they play the part, in short, of contour-lines. The width of the outcrops is determined, of course, by their position with regard to the configuration. Thus, upon a steep slope, an outcrop of a stratum many feet or yards in thickness will be indicated upon the map by a relatively narrow band or ribbon, while the outcrop of the same stratum occurring on the top of a hill would be represented by the whole surface of the bed, which might form quite a broad patch of colour on the map.

Inclined Strata. The outcrops of inclined strata also vary in direction with the shape of the ground, but they are influenced likewise by the angle of dip—an influence which becomes less and less marked as the dip increases. The width of individual outcrops similarly varies with the degree of inclination: beds dipping at a low angle yielding a relatively broad outcrop, while the same beds dipping at a high angle present a relatively narrow outcrop. Thus the outcrop of a bed of uniform thickness will appear broader or narrower as the dip diminishes or increases.

Vertical Strata. The outcrops of vertical beds are practically uninfluenced by the form of the ground, and display, of course, the true thickness of the strata.

Measurement of Thickness of Strata.—When strata are horizontal, it is obvious that their thickness can only be measured when they are exposed in section, as in sea-cliffs, river-valleys, etc. If we know the heights above sea-level reached respectively by the lowest and uppermost beds of a great series of horizontal strata, we of course know at the same time the thickness of the strata. So, again, in the case of vertical strata it is obvious that a line measured exactly across the strike of the beds will give us their thickness between any two selected points. But when strata are inclined, the width of their outcrop is necessarily greater than the actual thickness of the beds. By means of a protractor, however, there is no difficulty in measuring the thickness of a series of strata, inclined at a known angle between any two given points. Thus, in the diagram (Fig. 122), we have a series of beds dipping from A to B at an angle of 45°. The section is on the scale of 6 inches to the mile, so that the width of the outcrop between A and B is 880 yards, or half a mile. All that we need to do, then, is by means of a protractor to draw lines in order to show the exact inclination of the beds at A and B respectively;

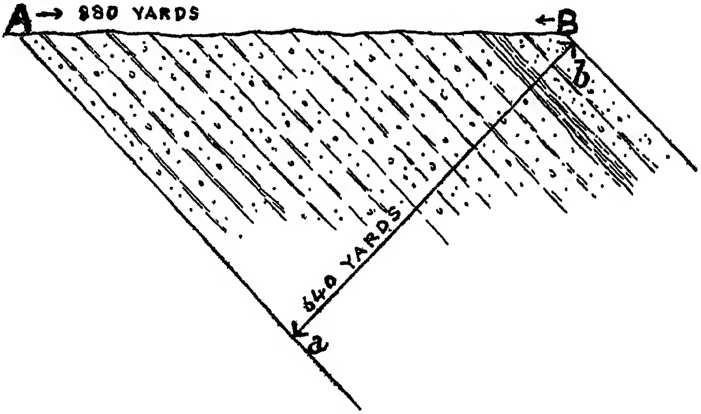
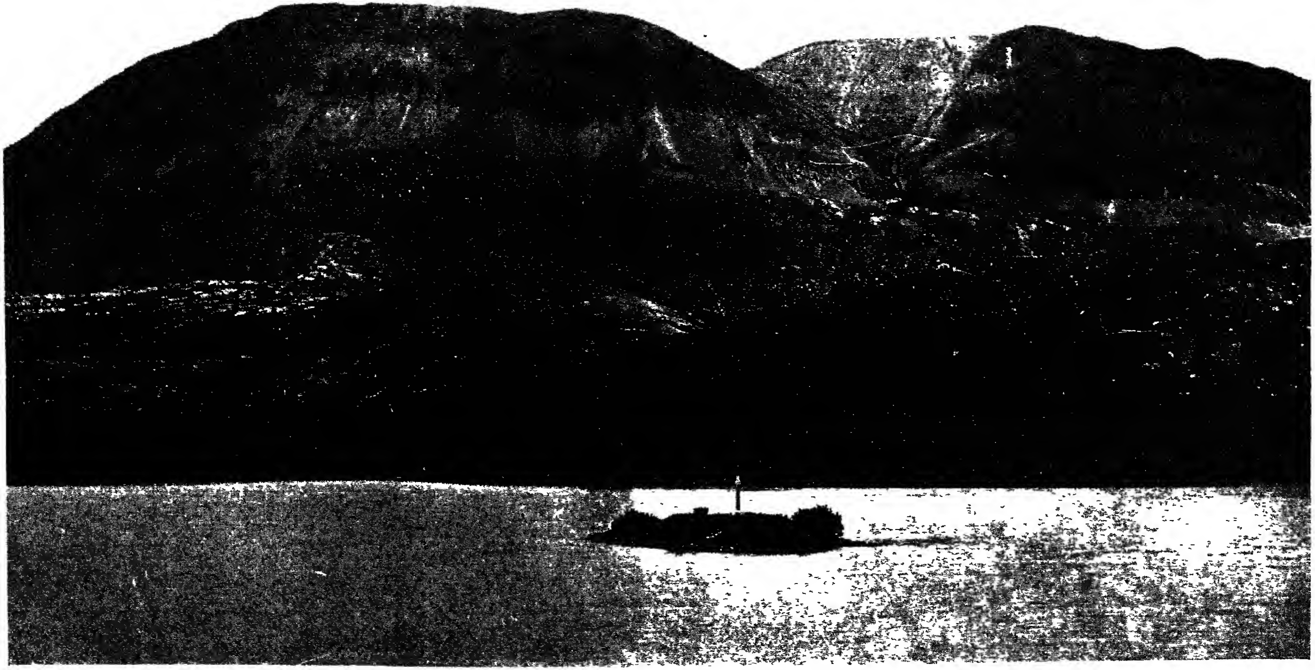


FIG. 122.—MEASUREMENT OF INCLINED STRATA.

PLATE LXI



Arkle from Loch Stack. The lower half of the mountain, and the intervening ground down to the lake, consist of Archæan Gneiss; the upper part of the mountain is white quartzite (Cambrian) resting unconformably on the gneiss.

Photo by H.M. Geological Survey.

[*To face page* 286

thereafter, another line drawn at right angles to the dip from *a* to *b* gives the thickness of the series (640 yards). From A to B the beds dip continuously at the same angle, but this is not very often the case; more commonly the dip is apt to vary in amount from place to place. When this is so, all we can do is to take the average angle of inclination, and from that we get approximately the true thickness.

The following rule, given by Charles Maclaren in his well-known *Geology of Fife and the Lothians*, may be found serviceable in estimating thicknesses in the field. If the breadth of inclined strata be measured across their outcrop at right angles to the strike, their true thickness will be equal to $\frac{1}{12}$th of their apparent thickness for every 5° of inclination. Or the rule may be put thus: divide 60 by the dip, and you obtain the fraction which expresses the thickness. Thus, suppose a series of strata measures across the strike 1200 feet—if the dip of the beds be 5° their thickness is $\frac{1}{12}$th, or 100 feet; if the dip be 10° the thickness is $\frac{1}{6}$th, or 200 feet; with a dip of 15° we get a thickness of $\frac{1}{4}$th, or 300 feet; and a thickness of $\frac{1}{3}$rd or 400 feet, when the dip is 20°. The rule is not correct when the dip exceeds 45°.

Thickening and Thinning of Strata.—When the observer has completed the drawing of his boundary-lines and outcrops, and clearly established the true succession of the strata, he will often find that the interval between the outcrops of two separate seams or beds varies from point to point. In other words, the intermediate strata seem to thicken out or to thin away, according as the outcrops are followed in one direction or another. Now this apparent increase or decrease may sometimes be accounted for, as we have seen, by inequalities of the surface, or by variations in the angle of the dip. If we have satisfied ourselves, however, that the mutual approach or retreat of the outcrops is not due either to the form of the ground or to increase or decrease in the degree of inclination, then we may include that it is owing to an actual thinning-away or thickening-out of the intermediate strata.

Unconformity.—This structure is readily revealed by mapping the ground, even although it may never be shown in any actual section. The accompanying diagram (Fig. 123) represents the ground-plan of an unconformity. Here there are two series of strata inclined in different directions

—one set is said to "strike at or against" the other. It is obvious that the series A cannot possibly belong to the series B. There is no room, so to say, for the beds A to swing round (between *a* and *x*) and dip underneath B. The junction between the two series must, therefore, be discordant and, if not due to faulting, can only indicate an unconformity. If the observer has reason to suspect an unconformity, he must carefully look for such evidence as is referred to in Chapter XII., where the phenomena of unconformity and overlap are described.

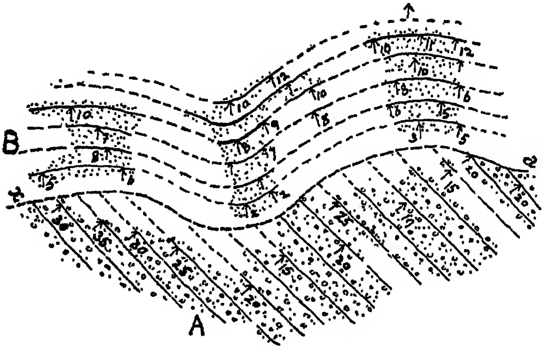


FIG. 123.—GROUND-PLAN OF AN UNCONFORMITY.
Continuous lines = outcrops and boundaries exposed in section. Interrupted lines = inferred positions of outcrops and boundaries. Stippling = rocks exposed at surface.

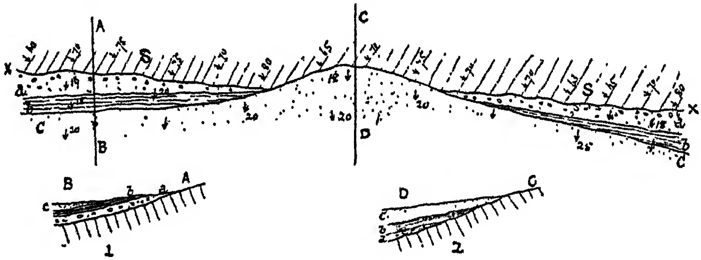
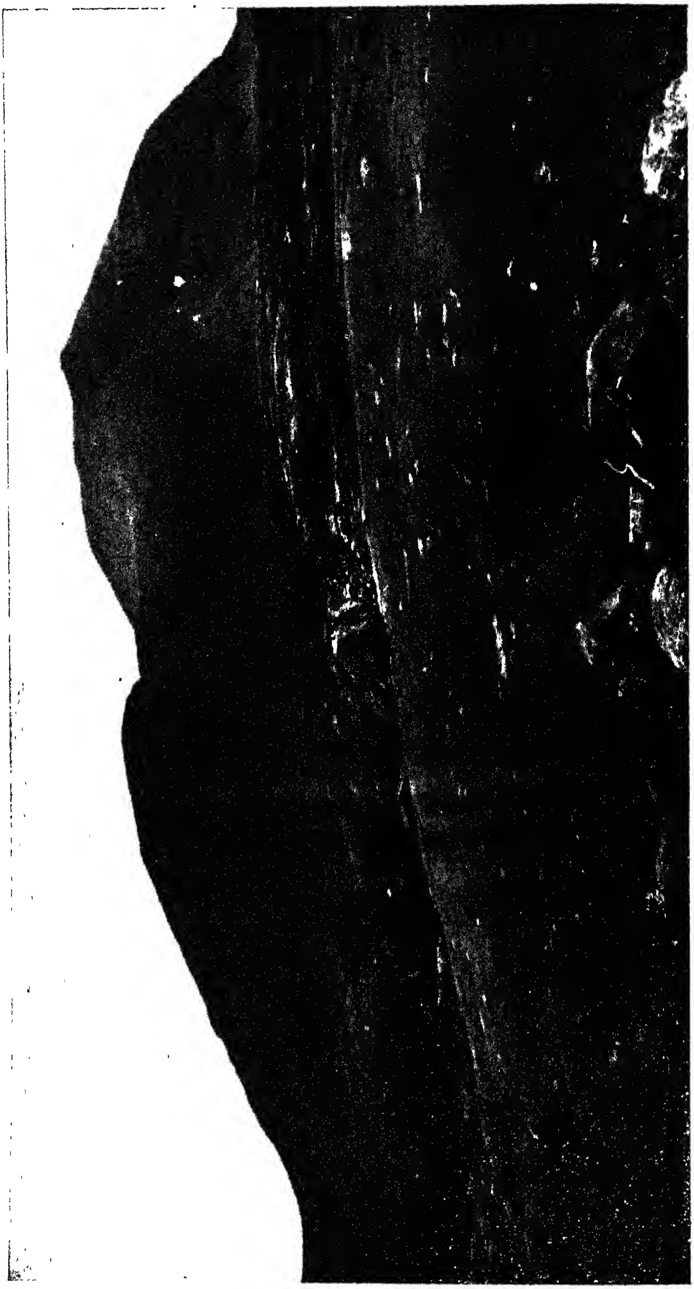


FIG. 124.—GROUND-PLAN OF UNCONFORMITY AND OVERLAP.
S S = Silurian strata; x x, unconformity; *a*, *b*, *c* = younger series of strata showing overlap; 1. Section along the line A—B; 2. Section along the line C—D.

Overlap is not readily shown upon a plan except when it accompanies well-marked unconformity. Mapping almost invariably discloses the structure, however, when it occurs on a considerable scale. Small local overlaps may readily be overlooked, but when the structure characterises a wide area it can hardly be missed. In Fig. 124, which is a ground-plan

PLATE LXII



GLACIATED ROCK-SURFACES, ACHNASHELLACH, ROSS-SHIRE.

Photo by H.M. Geological Survey.

[*To face page* 289

of an unconformity and overlap, the latter structure is not shown in the area traversed by the section line A—B. Here no appearance of overlap is apparent, but as the outcrops are followed towards the area C—D, the bed *b* gradually overlaps the bed *a*, while the former is overlapped by the sandstone *c* which comes to rest directly, and with a strong unconformity, on the highly inclined strata S—S. The section C—D shows the overlap and unconformity—*b* overlapping *a*, and being in turn overlapped by *c*.

Normal Faults.—Faults are not infrequently observed in natural sections, but these, as a rule, are small downthrows of little importance. The larger dislocations of a faulted region may now and again be encountered in railway-cuttings and other excavations, but they are rarely observed in natural rock exposures. One reason for this is obvious enough: highly shattered rocks are usually associated with great faults, so that when these are exposed by denudation the shattered materials readily fall asunder and the actual fracture becomes concealed. Or the shattered rocks on one or both sides of the fault being easily broken up and removed by epigene action, a hollow may be washed out along the line of dislocation, and form eventually a receptacle for alluvium and other products of surface erosion. Many faults fail to show at the surface of regions which, like our own, have long been exposed to denudation, simply owing to the fact that any inequalities of surface which may originally have been caused by such dislocations have long ago been planed away, and the ground has become more or less swathed in soils, subsoils, and superficial accumulations of every kind. Although denudation tends in this way to reduce a land-surface generally, nevertheless it is obvious that hard rocks will not be so readily reduced as soft rocks. Thus any marked or sudden change in the form of the ground will be due in most cases to an abrupt change in the petrographical character or the geological structure of the rocks. In most cases the low grounds will be composed of weakly arranged or of relatively soft rocks, while the higher ground will indicate the presence of harder rocks, or stronger structures better fitted to withstand the destructive action of epigene agents. As one frequent result of great faults is to bring relatively soft and hard rocks together, we may expect to find that such faults, although not actually seen in section, have yet influenced the form assumed by the ground under the influence of denudation—the hard rocks will tend to project above the level of the relatively soft or less durable rocks.

Abrupt changes in the form of the ground may be due, however, to other structures than faults—the more important of which are the following :—

(*a*) An abrupt change of level may be caused by the outcrop of a relatively durable stratum occurring in a series of less durable strata. In the annexed diagram (Fig. 125) we have the structure known as escarpment and dip-slope—one of the commonest forms of land-surface, especially in regions of moderately inclined strata. Now and again the dip of the strata, instead of being towards the high ground as in escarpment-structure, may be in the opposite direction. This occurs when a thick series of relatively hard rocks are overlaid by softer strata. The former, as in other cases, tend to form a line of heights; but the descent from these to the low grounds is usually less abrupt than in the case of escarpments (see Fig. 126). In both cases the lines of elevation caused by such outcrops may be either very sinuous or approximately straight—according as the strata are gently or steeply inclined. If an escarpment be due to the outcrop of such a rock as limestone it will usually extend for some considerable distance. If, on the other hand, it has been determined by the presence of a sill or a thick conglomerate, its lateral extension will probably be limited.

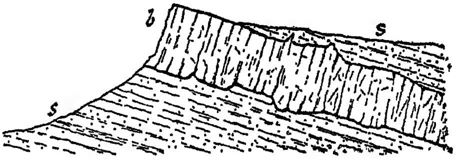


FIG. 125.—ESCARPMENT AND DIP-SLOPE.
b, dolerite ; *s*, sandstones and shales.

(*b*) A sudden change in the form of the ground may indicate an unconformity (see Fig. 123), where a series of "soft" rocks (B) repose on the truncated ends of much older and more indurated strata (A). In a case of this kind the line of high ground will usually be more or less sinuous and irregular, for it simply represents a former coast-line, the younger rocks ever and anon extending into what were old bays and inlets. Evidence of so well-marked an unconformity as this could hardly escape an observer; but in nature the proofs of unconformity are not always so conspicuous.

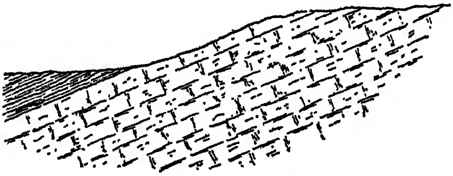


FIG. 126.—INCLINED "SOFT" ROCKS OVERLYING "HARD" ROCKS.

The observer who encounters a sudden or abrupt change from low to high ground, and has satisfied himself that the form of the surface cannot be explained either by the occurrence of interbedded hard rocks, of intrusive rock, or of an unconformity, will be justified in suspecting the presence of a fault. If a fault be present, then the line separating low and high ground will be somewhat straight or very gently sinuous, while seepage of water and more or less numerous springs will probably occur, and so indicate the position of the actual line of fracture. When the presence of a fault is thus suspected, the field-geologist will carefully search for the more direct evidence, some account of which has been given in Chapter XI. The fault itself, if it be one of considerable displacement, will probably not appear in section; but he may find that the strata seen in the low ground become more or less abruptly turned up at high angles of inclination as he approaches the base of the hilly ground, until, at last, they may stand on end. Should such be the case, the strata so disturbed will probably be abundantly shattered and traversed in all directions by irregular joints, the faces of which will frequently show slicken-sides and be coated with mineral matter. In short, veins of quartz, calcite, etc., may ramify more or less abundantly through the disturbed rock-masses. When the strata on both sides of the inferred fault are mapped, the observer will most likely find that the two sets of rock "strike at" each other—the outcrops of one, or it may be of both series, being truncated, as shown in the above ground-plan (Fig. 127). The determination of the downthrown side of a very large fault is seldom doubtful. If the relative age of the strata on either side of the dislocation be known, and this is usually the case, the younger rocks will, of course, occur on the downthrow side. In cases where faults

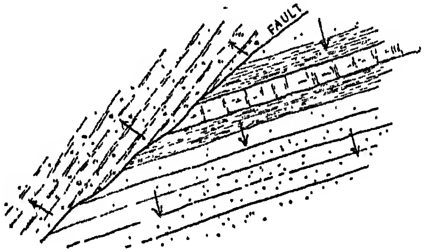


FIG. 127.—FAULTED STRATA STRIKING AT EACH OTHER.

traverse one and the same series of rocks, and are not exposed anywhere in section, the downthrow side of a dislocation will yet be rendered evident by the effect produced upon the outcrops, as already described (Chapter XI.).

Reversed Faults.—Reversed faults occurring amongst strata the geological age of which is known are not hard to detect. When Carboniferous rocks, for example, are seen dipping regularly underneath Devonian beds, it is obvious that this inversion of the stratigraphical succession must be due either to overfolding, or to an overthrust, or to a combination of both structures. If the inversion be the result of folding alone, then it is obvious that both series of rocks occurring in the reversed limb of a strongly inclined or recumbent fold must be turned upside down. If, on the other hand, the inversion has been caused by a reversed fault alone, then there will be no overturning of the beds in either series of strata, the individual beds of the Carboniferous will occur in regular sequence, and the same will be the case with the Devonian strata. But, as reversed faults have frequently resulted from the yielding of inclined folds, it often happens in cases of inversion that this structure shows a combination of overturning and overthrusting.

Folding and faulting of such extreme kinds are usually best developed in regions which have been subject to great deformation—regions the structural geology of which can hardly be unravelled by the tyro. The observer, who is prepared to work out complicated structures like those of N.W. Scotland, the Alps, etc., has got far beyond the need of an elementary hand-book. The beginner, however, who is anxious to become familiarised with the phenomena likely to be encountered in regions of complex structure, can hardly do better than study the beautiful maps of Wester Sutherland and Ross, which have been issued by the Geological Survey. With these maps before him, and with the help of the works mentioned in the footnote, the student will have some idea of the nature of rock-structures which are characteristic of "folded mountains." *

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* The sheets of the 1-inch map are as follows:—81, 91, 101, 107, 114. The whole region is described in great detail in the Geological Survey's Memoir—*The Geological Structure of the North-West Highlands of Scotland*, 1907. The beginner, however, should consult especially the following:—(a) *Guide to the Geological Model of the Assynt Mountains*, by B. N. Peach and J. Horne, 1914; (b) *Geological Map of the Assynt District* (Parts of Sheets 107, 108, 101 and 102), 1923, published by the Geological Survey; and (c) *Geological Guide to the Assynt District of Sutherland*, by M. Macgregor and J. Phemister, 1937, published by the Edinburgh Geological Society.

Eruptive Rocks.—The mapping of eruptive rocks is carried on in the same way as that of sedimentary strata. The outcrops of contemporaneous or effusive igneous rocks are not more difficult to follow than those of limestone or any other bedded rock. The boundary-lines of intrusive bosses, sills, and dykes, however, are more irregular, and, in the absence of sections, may sometimes be hard to trace. Rocks of this class, however, are usually more resistant than the rocks they traverse, and thus tend to project and form conspicuous features at the surface. In mountainous regions where the rocks are generally well exposed, the field geologist is more likely to be troubled with the abundance than with the paucity of the evidence. In the case of a mass of granite, for example, the junction-line is apt to be very irregular—larger and smaller veins penetrating the adjacent rocks in all directions. The details of structure are often, indeed, so intricate that the most the observer can do is to generalise these, drawing his lines so as to show the shape of the mass—whether it be circular, elliptical, or quite irregular, or following in a rude way the strike of the surrounding rocks. The numerous veins, etc., must be generalised, but when well exposed in section or in plan, it is advisable to make careful drawings of these for future reference, when the phenomena come to be described. So far as he can do so, the observer will try to indicate upon his map the nature of the altered rocks which surround the granite. The stages of contact-metamorphism, however, so frequently graduate into each other, that it is often quite impossible to draw boundary-lines separating one kind of metamorphic rock from another. Nevertheless this can sometimes be done, more especially in cases where the original unaltered rocks have differed markedly in character, and have thus been metamorphosed into more or less strongly contrasted sub-crystalline and crystalline rocks. There are many other observations that the field-geologist will find it impossible to indicate upon a map, but which he should not fail to describe in his note-book.

Sills are not, as a rule, hard to trace. Even when the actual lines of junction with adjacent rocks are not exposed, the intrusive character of a sill is frequently indicated by the way in which it seems to steal across the strike of the strata. The absence of any bedded tuff accompanying the igneous rock would be so far suggestive of the intrusive character of the latter. This negative evidence, however, would be much strengthened if veins of the same kind of rock were found penetrating the overlying strata. We could hardly doubt in that case that the veins were genetically connected with the igneous rock, and that the latter, therefore, was not truly bedded but an intrusive sheet or sill. *Dykes* are even more readily diagnosed in the field than sills, and can usually be followed without difficulty. Their presence is often revealed by lines of springs which come to the surface on that side of a dyke towards which the strata are inclined. For the various details of structure and the general phenomena characteristic of sills and dykes, however, reference should be made to Chapter XIII.

An account of *Necks* or pipes of eruption is given in Chapter XIV. When these structures are seen either in plan or in section, their character is at once revealed. Sometimes, however, the actual line of junction between them and the rocks they traverse is entirely concealed, and in such cases they might possibly be mistaken for outliers. Fig. 128, for example, shows, in ground-plan, field data which are so apparently incomplete that the agglomerate and tuff, *a*, might be explained as an outlier resting unconformably upon the truncated ends of the strata *b*. We should have no doubt, however, as to its intrusive nature if we could make the following observations :—1. The tuff either shows no bedded arrangement, or, if any trace of bedding be visible, the dip of the rude layers is towards the centre of the mass. 2. Dykes or veins of crystalline rock traverse the tuff, while similar veins of the same rock appear at some little distance invading

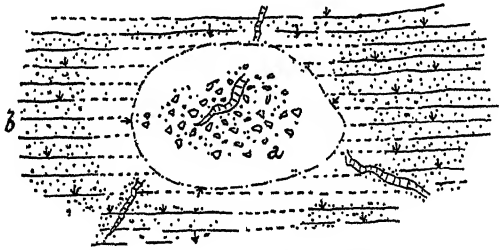

FIG. 128.—GROUND-PLAN OF NECK.

Continuous lines and arrows = boundaries and dips exposed in section. Interrupted lines = conjectural positions of boundaries. Stippling, etc. = rocks exposed at surface.

the adjacent rocks. 3. The surrounding strata as they approach the tuff are more or less shattered, and perhaps show traces of induration as if from the action of heat. Should the portions exposed be not far from the concealed junction, the beds may appear suddenly to bend over so as to dip abruptly towards the agglomerate or tuff. 4. Fragments of the adjoining rocks and of rocks which may be recognised as belonging to lower and higher geological horizons, can be detected in the tuff. Evidence of this varied kind would satisfy us that the igneous rock was not an outlier but a neck, and we should be justified in drawing around it an interrupted line.

Occasionally, necks are occupied wholly by crystalline rock, the junction between which and the adjacent rocks may similarly be concealed, so that the observer may be in doubt at first as to whether the igneous rock may not be an isolated patch or cake resting unconformably on the strata that crop out in its immediate neighbourhood. Were such its origin, its jointing should be vertical. On the other hand, if it be of the nature of a plug occupying a pipe of eruption, the joint-planes will be arranged horizontally. A geologist having satisfied himself on this point would, of course, seek to strengthen the evidence by such additional observations as are referred to above in connection with necks of agglomerate.

Slaty-Cleavage.—This structure, we have seen, occurs among rocks which have been more or less folded and compressed. In fine-grained slates the original planes of lamination and bedding are usually obscured, and may even be entirely obliterated, and when such is the case the superinduced cleavage-structure might readily be mistaken for planes of sedimentation. The geologist, therefore, must be on his guard, and when any thick belt of finely divided argillaceous rock is encountered in a region of steeply inclined and much-folded strata, he should at once suspect that the division-planes may be those of cleavage. If the rock be really a slate, careful examination will probably result in the detection of the original lines of bedding. These may be indicated by alternating bands of differently tinted slate or by variations in the texture of the slates—such differences of colour and texture being visible in section, as it were, on the cleavage-planes. By splitting the slate open we can see that the varying tint and texture are not merely superficial but, penetrating the rock, are as conspicuous on one face of the slate as on the other. Usually, however, bands and beds of greywacké, quartzite, or other less cleavable rock occur interbedded with slates—and the presence of these at once discloses the true bedding. It is not uncommon, moreover, to find the cleavage-structure restricted to the argillaceous rocks of a series of folded strata, and as the structure in question frequently traverses the original bedding-planes at a high angle, the junction between cleaved and non-cleaved rocks often resembles an unconformity (Fig. 129). In mapping slates, therefore, the chief danger to be avoided is the mistaking of cleavage for bedding. It is necessary, however, always to note the direction of the strike and dip of the cleavage-planes, especially when the bedding is obscure or obliterated. For the strike of the cleavage coincides more or less closely with the axes of folds and plications, and is thus helpful in unravelling the geological structure of a complicated region.

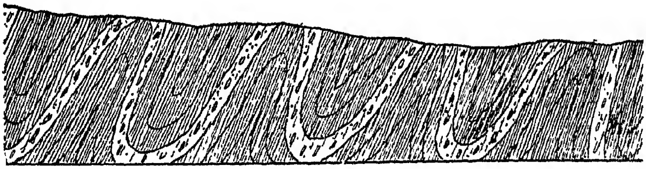

FIG. 129.—CLEAVAGE AND BEDDING.

Regional Metamorphism.—Not much need be said on the subject of mapping an area in which regional metamorphism has been developed—the structural geology being frequently highly complicated and obscure, and hardly to be attempted by one who is not well versed in petrography, and has had little experience in geological surveying. Nevertheless, even a beginner will find much to interest him in trying to puzzle out the structure of such a region.

We have already learned that regional metamorphism is not infrequently a result of deformation. In other words, the rocks of such a region have been more or less compressed and buckled up or folded, and in many places have yielded to tangential squeezing and crushing, whereby overthrusts on a grand scale have often been effected. In mapping an area which exhibits such phenomena, it is obviously most important that we should be able to lay down the axial lines of the chief folds and the position of all considerable thrust-planes. This may be done without troubling ourselves at first as to purely theoretical questions concerning the particular chemical and mineralogical changes through which the rocks may have passed. It is more than likely, however, that as we proceed with our field-observations we shall be confronted with evidence that may go a long way to show not only what the original character of the rocks may have been, but to reveal the successive changes which some of them have undergone.

Bearing in mind, then, that the rocks, whatever their original character may have been, are arranged in folds, we shall expect to find the position of these indicated by the outcrops of more or less persistent zones or belts of different kinds of schistose rocks, all having approximately the same trend. These bands, we may safely assume, represent the general strike of the series. Not infrequently, however, we may traverse wide areas throughout which only a monotonous succession of one and the same kind of rock may appear. Nevertheless, if our traverses be sufficiently extensive, we may expect ere long to meet with other types of rock, the relative position of which will enable us to determine the general strike or alignment of the whole complex. The observer must be on the constant outlook for bands of rock which are characterised by the presence of minerals peculiar to themselves. Knowing that the production of these minerals is due in all probability to some peculiarity in the composition or constitution of the original rocks, their presence may sometimes be as useful in working out a stratigraphical succession as the occurrence of fossils in a series of unaltered strata. Beds and bands of ores not infrequently occur in connection with particular kinds of schist, and have in certain regions, as in Norway, been followed over wide areas; and as these ore-bearing rocks are everywhere associated with the same kinds of schist, there can be no doubt that they are truly stratiform and indicate a definite geological horizon. Crystalline limestones and dolomites interbedded with certain distinctive kinds of schist have in like manner often been traced for long distances, and when similar calcareous bands accompanied by the same varieties of schist are found cropping out at what might appear to be either lower or higher horizons, the probabilities are that such successive outcrops are simply the result of folding, the same beds coming again and again to the surface.

It is not unlikely that the observer, while traversing a region of schistose rocks, may occasionally encounter areas of less highly metamorphosed strata. He may be able to recognise well-marked clastic rocks, such as schistose conglomerate, quartz-rock, phyllite, greywacké, limestone, etc. Should such be the case, the strata must be carefully followed along and across the strike, for the purpose of tracing the changes they undergo as the region of more highly metamorphosed rock is approached. The successive bands or zones of distinctive schists which we may already have traced through this latter region, we may now be able to connect with particular beds occurring in the area of less altered rocks. Should such be the case, we shall have no reason to doubt that the schists are metamorphosed sedimentary strata; and should the direction of their foliation coincide with the dip of the individual bands, we shall be justified in concluding that the schistose structure has been developed along original planes of bedding. This is most likely to be the case when isoclinal folds have been closely compressed, so that the rocks are either on end or disposed in highly inclined positions. When the folds open out, foliation—often following planes of cleavage—must sometimes have coincided with, and sometimes have traversed, the original bedding at various angles. Therefore, the mere direction of the planes of foliation, when all trace of bedding has been obliterated, cannot, in the absence of other evidence, be relied upon as revealing original stratification.

Just as the observer must be on the outlook for every item of evidence that seems to indicate the arrangement of metamorphosed strata, and to reveal the original character of the beds, so he must endeavour to ascertain what relation the eruptive rocks he may encounter bear to the schists they traverse. If they are older than the metamorphism, then they themselves will have undergone some change, and may be as highly crushed and foliated as the schists. If, on the other hand, they are of later date, they will not be metamorphosed. Possibly the geologist may encounter igneous masses of older date than the metamorphism which, nevertheless, have a normal appearance. When such masses, however, are followed for any distance they will doubtless begin to show traces of crushing, and eventually pass into schists or gneisses as they near the region of extreme metamorphism.

Both normal and reversed faults may appear among schistose rocks—indeed, faults and extensive thrust-planes may almost be expected to occur. As the outcrops of thrust-planes usually follow the strike, they are sometimes hard to detect unless they be on a grand scale. But if the observer has been able to make out the general geological structure, and has ascertained that the schistose rocks show a more or less definite succession, careful mapping will reveal all the reversed faults of any importance. Frequently, indeed, these give rise to prominent features at the surface, following as they do some determinate direction athwart the face of mountain slopes, where they simulate the appearance of horizontal or inclined bedding-planes. Thrust-planes are usually rendered conspicuous by erosion. Naturally, they often bring into juxtaposition rocks of very different kinds—on one side, it may be, massive and relatively durable rocks; on the other side, more readily disintegrated and degraded materials. Not infrequently, therefore, thrust-planes are laid bare by the removal of the softer rocks from the inclined surface of harder rocks upon which they rest. Or, in cases where a gently inclined thrust-plane has brought harder or more durable rocks to rest upon less resistant rocks, an escarpment may be developed by erosion, the geological structure producing the same effect as the intercalation of a relatively "hard" bed in a series of "softer" strata. Occasionally, running water has hollowed out deep gullies and ravines along the outcrops of thrust-planes. The presence of a considerable thrust-plane is often further revealed by the crushed and brecciated appearance of the immediately adjacent rocks. So shattered may the rocks be, that the line of movement often resembles the outcrop of a breccia. Still more notable are the evidences of metamorphism induced by such great rock-displacements. Clastic rocks, for example, may be rendered crystalline and schistose, the foliation extending upwards for some little distance above the plane of rock-movement. Massive crystalline eruptive rocks may, in like manner, be crushed and foliated, while ancient gneissose and schistose rocks become similarly modified, new planes of foliation being developed, which may cross the older foliation at any angle. It is particularly noteworthy that the younger foliation always coincides in direction with the plane of rock-movement.

The system of thrust-planes, traversing schistose and other rocks in a region of highly complicated structure, is often cut across by one or more systems of normal faults, which shift the thrust-planes just as if they were outcrops. Such faults, therefore, can be detected and followed in the usual way.

CHAPTER XX

GEOLOGICAL SURVEYING—*continued*

Mapping of Unconsolidated Tertiary Deposits, and of Glacial and Fluvio-glacial Accumulations—Boulder-clay; Roches Moutonnées; Terminal Moraines, etc. Raised Beaches. Lacustrine and Fluviatile Deposits. Peat.

Superficial Accumulations. — In this and other countries the "solid" rocks are often concealed under sheets of unconsolidated materials, as gravel, sand, loam, clay, etc. Sometimes these superficial accumulations are confined to valleys and depressions, or they may mantle the entire surface of broad, low-lying lands. They are of very various origin—marine, fluviatile, lacustrine, terrestrial—some dating back to early Tertiary times, while others belong to later periods, and many are still in process of formation.

The TERTIARY sedimentary deposits of this country, owing to their generally unconsolidated condition, their inconsiderable thickness and limited extent, may be looked upon as "superficial accumulations." They are chiefly marine, and practically confined to circumscribed areas in the south-east and south of England. On the Continent, however, they cover much more extensive areas—in some of which the deposits are essentially of marine origin, while in other regions they are freshwater, or may consist of an alteration of marine and freshwater accumulations. In North Germany, Belgium, France, and England, the beds are arranged in approximately horizontal positions—the marine and fluvio-marine deposits occurring for the most part in maritime districts, and seldom reaching more than a few hundred feet above the sea. The deposits vary much in character—in some places consisting largely of clay or marl, in other places of sand or gravel. These old sedimentary formations, since the time of their elevation, have been subjected to very considerable erosion; but, owing to their generally unconsolidated character, they are not distinguished by any very prominent surface features, forming, for the most part, gently undulating low grounds and plains.* The mapping of such accumulations is attended with some difficulty, it being often hard to trace the outcrops. This is due, in the first place, to the fact that upon slopes the junction-lines are obscured by the washing down of materials from above—the outcrops of lower beds being often entirely concealed under sand, loam, etc., derived from overlying strata. Geologists mapping in such regions occasionally employ a gouge-like spud, which might be described as a kind of exaggerated "cheese-taster," for the purpose of ascertaining the position of the concealed outcrops as accurately as possible. The annexed diagram will serve to illustrate the *modus operandi* (Fig. 130). The surface from *x* to *b* shows nothing but sand, we shall suppose, while between *a* and *x* clay obviously immediately underlies the soil. The observer having reason to believe that the sand at *x* and for some distance up the slope is not *in situ* but *remanié*, forces his instrument at intervals down through the sand, until he reaches a place where his borer no longer touches the clay. Unless the amount of sand carried down the slope be very great, it is obvious that the observer can by such means attain a line for his outcrop which cannot be far from the truth.

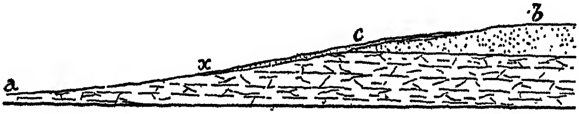

FIG. 130.—CONCEALMENT OF OUTCROP BY SURFACE WASH.
Clay (*a*) overlaid by sand (*b*).

In low-lying regions of Tertiary deposits, clear natural sections are of infrequent occurrence—the best exposures being met with along sea-coasts and in recent artificial cuttings and excavations. Frequently, indeed, the geologist is largely beholden to the records of deep well-borings, etc., for information with regard to the succession of the strata and the probable position of the outcrops. Many hints he will doubtless derive from a careful study of the various soils and the character of the vegetation, and even from the form of the ground. Gravel, for example, being a highly porous deposit rapidly absorbs rain, and is, therefore, less liable to be washed down and trenched by running water, while impervious clay, on the other hand, is readily attacked superficially. The former deposit, therefore, will often tend to form dry lands with a gentle or more rapidly undulating surface. Thick sands, in like manner, will give rise to somewhat similar dry rolling ground ; while clays may form low plains or higher tracts trenched in all directions by running water. But in countries which, like our own, have been long under cultivation, the soils of a Tertiary district are often so transformed that it is hard to tell from them what the precise nature of the subjacent deposits may be. For the same reason, plant-associations in such areas cannot always be trusted as guides by the geological surveyor. Such difficulties, however, are only likely to happen when the geologist is dealing with the outcrops of relatively thin accumulations—when, on the other hand, a stratum or series is thick and covers wide areas, the nature of the soil and the character of the vegetation will help the observer to trace its extent with more or less confidence. Speaking in general terms, we may say that the mapping of unconsolidated Tertiary deposits is carried on in much the same way as the tracing of consolidated sedimentary strata. Now and again they are gently folded and assume a basin-shaped arrangement, and when such is the case the outcrops are not so hard to trace.

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* The Tertiary deposits which in England and the low grounds of Middle Europe generally are usually unconsolidated and not much disturbed, spreading as sheets of greater or less thickness over Mesozoic and older rocks, are represented in Southern Europe by much more massive strata, the older portions of which enter largely into the framework of the Pyrenees, the Alps, the Apennines, etc. It would be an abuse of terms to speak of these deposits as "superficial formations." Even in this country, where the corresponding deposits are of slight thickness and more or less unconsolidated, they are, nevertheless, not usually included by geologists amongst "superficial formations"—this term being restricted to post-Tertiary and recent accumulations alone.

GLACIAL AND FLUVIO-GLACIAL ACCUMULATIONS. The deposits included under this head are widely distributed in this country and in corresponding latitudes of the Continent and North America. They cover extensive areas in our lowlands—occupying valleys and sweeping over intermediate tracts, so as largely to conceal the underlying solid rocks. In our mountainous districts they are mostly restricted to the valleys, but often extend upwards to considerable heights upon the mountains themselves. It would be quite beyond the limits of this work to attempt any detailed description and classification of these accumulations. Attention is therefore limited to some of the salient phenomena presented by the more notable of the deposits in question.

(a) *Boulder-clay or Till.* This is an unstratified or amorphous mass, the essential lithological characters of which have already been given (see p. 69). One of its most striking peculiarities are the stones and boulders which it contains. These are almost invariably fresh, unweathered, and generally blunted and subangular in shape, often showing smoothed, polished, and striated faces. The beginner should note especially the character of the striation and its relation to the shape, size, and species of the stones. Usually, stones which are longer than broad are most distinctly striated lengthways, while those which are as broad as they are long are striated equally in all directions; very large blocks are often smoothed on one side only, while smaller boulders and stones are commonly smoothed all over; again, compact fine-grained rocks, such as limestones, shale, ironstone, felsite, etc., have usually received a better polish than coarse-grained grits, sandstones, etc. The observer should be on the outlook for any traces of arrangement of the stones and boulders. Occasionally, lines of small and large boulders may be seen traversing the face of a cutting in boulder-clay, the boulders not infrequently lying lengthways. Sometimes the upper surfaces of such "striated pavements," as they are termed, are distinctly striated in one common direction. The student should also subject the gritty clay itself to a close examination. A portion should be taken home and thoroughly dried and crumbled down, when the shape and nature of the larger fragments can be studied with the help of a lens. These will be found to be simply minute boulders, angular, subangular, and often striated and quite unweathered. The "clay" may be still further reduced by shaking it in water and passing it through a sieve. By using sieves of various degrees of fineness, all the gritty particles above a certain size may be sifted out, and only an extremely fine-grained residue be left. The grit, examined microscopically, is found to resemble in every respect, save size, the small fragments which the student may have determined with the aid of his pocket-lens. They all alike consist of fresh, unweathered mineral matter. The residue which is not separated by the finest meshed sieve may be reduced by shaking it in water and allowing it to settle. From the turbid water a sediment is gradually thrown down. The water which still remains clouded can then be decanted and allowed to stand until it clears. In this way we obtain a still finer grained mechanical precipitate. These sediments are of precisely the same character as the gritty materials separated by the sieve—they are fresh and unweathered, being composed of what may be termed "rock-flour," one chief constituent of which is powdered quartz. It is this "rock-flour" that forms the major portion of the so-called boulder-*clay*—the proportion of true clay throughout the mass appearing to be relatively insignificant. Indeed, according to Professor Crosby, "till in its natural condition is often less than one-tenth and rarely more than one-eighth pure clay."

Boulder-clay is believed to be the bottom- or ground-moraine of massive glaciers or ice-sheets, and to have been formed by the crushing and grinding action of ice in motion. Formed and accumulated under these conditions, we can readily understand why it should consist essentially of fresh unweathered rock-materials. But it is beyond the purpose of these notes to give any particular account of this remarkable formation. It may, however, be of service to the field-observer to indicate certain points which ought to be noted when he begins to map in a till-covered region. First, then, the configuration of the surface should be considered. Sometimes the ground in such a region is devoid of any prominent feature, rising and falling in long, gentle undulations, that may not trend in any particular direction. In other cases the surface is more diversified and may show a pronounced "corduroy" or wrinkled configuration, being marked by a series of longer and shorter parallel and often interosculating banks with intervening hollows. The trend of these *drums*, or *drumlins* as they are called, should be carefully noted. In most cases the banks in question appear to be original, *i.e.*, they are forms assumed by the boulder-clay while it was being accumulated. Occasionally, however, they are simply the result of the unequal erosion of a gently undulating or plain-like surface of boulder-clay.

The colour of the till and the nature of its included stones and boulders should be noted. The colour will usually be found to correspond with that of the predominant rock or rocks of a district; it is therefore *local*. The most abundant rock-fragments in the till are also generally local, but commingled with these many others of more distant derivation are sure to occur. The observer should take percentages of the different kinds of rock and endeavour to ascertain their several sources. If he be a beginner he will naturally be at fault, but a good geological map of the country will afford him some help, and he may obtain more by examining the rock-collections in public museums. Should he be able to determine the source of many of the stones which are "strangers," this will give him a strong hint as to the general direction followed by the old *mer de glace*.

Lenticular layers and sometimes thicker series of unfossiliferous gravel, sand, and laminated clay may occur underneath, and are still more frequently included in boulder-clay. Such deposits are often more or less confused and disturbed. They obviously point to the action of subglacial water. The boulder-clay that immediately underlies them will be found quite fresh and unaltered, showing that it has never been exposed to the oxidising influence of the atmosphere. Now and again, however, stratified deposits of gravel, sand, loam, marl, peat, etc., are met with resting upon and covered by boulder-clay. The boulder-clay underneath such beds is almost invariably discoloured for some distance downwards, thus showing that it must for some time have been acted upon by the atmosphere and surface water. The stratified deposits in question have often yielded relics of an old land-surface, and are thus evidence that the formation of boulder-clay was an interrupted and not a continuous process. The same inference may be drawn from the occurrence of marine fossiliferous deposits included in till.

The relation of the boulder-clay to the immediately subjacent rocks is deserving of study. The latter are sometimes so broken, jumbled, and confused, that it is hard to say where the shattered and disturbed rock ends and boulder-clay begins. The student should note whether the slabs and reefs of rock have been bent over or wedged out of their beds, and the direction in which they have moved should be ascertained. Instead of being broken and jumbled, the subjacent rocks may show a smoothed, polished, and striated surface. The compass-bearing of the striæ should always be taken, as this indicates precisely the direction of ice-flow at the point of observation. It is possible that the beginner may at first have some difficulty in distinguishing between a glacially striated surface (Plate LXIII.) and slickensides (Plate XXXVI.). The latter, however, are usually confined to flat or even

PLATE LXIII

GLACIALLY-STRIATED SURFACE OF SLATES, KILCHIARAN, ISLAY.

Photo by H.M. Geological Survey.

[*To face page* 304

surfaces, and are frequently glazed with mineral matter; the scratches, moreover, are strictly parallel. It will be noted further that when a slicken-sided surface shows any depressions these are not striated. Glacial striæ, on the other hand, may occur on flat, convex, concave, or rapidly undulating surfaces. The smoothing and polishing is not confined to the protuberances upon a rock-surface, but every little dimple and depression is equally dressed. Although roughly parallel, glacial striæ are yet not so straight as slickensides, but often cross each other at acute angles. Frequently, indeed, they may be seen curving gently round the sides of projecting knobs as if these had caused some slight deviation of the ice-flow. The scratches may be as fine as if drawn by an engraver's needle, or they may be coarse, jagged ruts; and between these extremes all gradations occur and may be seen side by side on the same rock-face.

Roches moutonnées. Dressed rock-surfaces occur not only underneath boulder-clay but on exposed hill-slopes and rocky elevations, from which the boulder-clay has been stripped by denudation, and in many places also where probably no boulder-clay was ever deposited. The observer should take particular note of the configuration of the hills and mountains of a glaciated region (see Plate LXII.). Land which has been subjected to extreme glaciation generally shows flowing contours. Projecting prominences and crags are smoothed and rounded off on the side that faced the ice-flow; while the opposite side, protected by its position, may retain its original roughness. The smoothed face is termed the *Stoss-seite*, and the non-glaciated face the *Lee-seite*. Whole mountain-slopes may exhibit a rudely mammilated surface, the rounded rock-surfaces being often striated. Sometimes the ice-markings are fresh and readily recognisable; at other times they have almost vanished—the mere "ghosts of scratches." Even when they have disappeared, however, the mammilated outlines of the rock-masses are cogent evidence of the former presence of glacier-ice. These rounded hummocks or *roches moutonnées*, as they are called, generally indicate clearly enough the direction of ice-flow. In the case of abrupt crags and tors the stoss-seite is usually steep, while the lee-seite assumes the form of a long sloping ridge. This phenomenon is known as *crag-and-tail.* Sometimes the tail is composed entirely of glacial detritus (boulder-clay, gravel, etc.).

More frequently (especially when the crag is very prominent and of considerable dimensions) the "tail" consists largely of solid rock, usually covered with a less or greater thickness of boulder-clay, etc.

Terminal Moraines: Perched Blocks, etc. In many of our mountain valleys, angular blocks and earthy débris are sprinkled more or less abundantly over the ground, up to very considerable elevations. In the bottoms of the valleys, knobby ridges, mounds, and hillocks, composed of the same materials, are of common occurrence (Plate LXVII.). The character of the deposits, the peculiar shape of the hillocks, etc., and their position, are comparable in all respects to similar phenomena occurring in the glacier-valleys of alpine regions. There can be no doubt that they are the *terminal moraines* of extinct glaciers. Low ridges or banks, or lines of morainic débris running along the mountain-slopes of many highland valleys, correspond to the *lateral moraines* of existing glaciers. *Perched blocks* are erratics which have been carried by the ancient glaciers, and successively stranded as the great ice-flows melted away (Plate LXII.).

Sheets and Mounds of Gravel and Sand. Throughout wide areas, boulder-clay is often more or less deeply buried under gravel and sand. These deposits may assume the form of extensive sheets with a gently undulating surface; or they may occur as long curving and irregularly winding ridges; or as tumultuous groups of closely associated mounds, hummocks, and ridges, known as *kames*. Sometimes the accumulations consist principally of fine sand—often diagonally bedded—or of interbedded sand and laminated clay. In other places, sand and gravel are equally prominent, while elsewhere coarse shingle and boulders are most abundant. At rarer intervals a mound or ridge may be composed of rude morainic débris—a rubble of angular blocks and rock-rubbish.

It is obvious that deposits so heterogeneous could not all have been formed in quite the same way; and it would be out of place here to discuss the various views which have been entertained as to their origin. The general belief, however, is that all the deposits in question were accumulated while the old icy covering of the land was gradually melting away. The observer will note that the long winding ridges (known as *eskers*) are composed chiefly of gravel—often very coarse—with more or less numerous boulders. They have obviously been laid down by torrential water; and when good sections across an esker are exposed, the stones sometimes show that imbricated arrangement which one may often observe amongst the stones and coarse shingle of streams and rivers (Fig. 131). Many geologists incline to the belief that these eskers mark the sites of subglacial torrents by which the great *mers de glace* were tunnelled, especially during the period of their final dissolution. In the low-lying parts of the country, numerous wide sheets of sand and gravel seem also to have been accumulated underneath the melting ice-flows, for they are often closely associated with eskers. In other cases, however, they may have been distributed over the exposed surface of the low lands by water escaping from the gradually disappearing snow-fields and decaying glaciers of adjacent high grounds.

In hilly and mountainous tracts, narrow and broad terraces and considerable plateaus of gravel, sand, and clay obviously mark the sites of ancient glacier-lakes. Such are the Parallel Roads of Glenroy, the wide sand-plains covering the watershed between the rivers Avon and Irvine in the neighbourhood of Loudoun Hill, and many similar terraces and flats occurring in the Northern Highlands and Southern Uplands. Even the hill-slopes overlooking the broad low-land tracts of Scotland now and again show strong evidence of the former presence of temporary glacial lakes, which appear to have come into existence after the hills in question had been divested of their icy covering, and while the adjacent lowlands were still thickly mantled by the gradually decaying *mer de glace*.

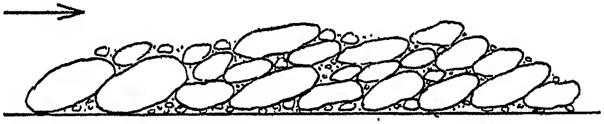


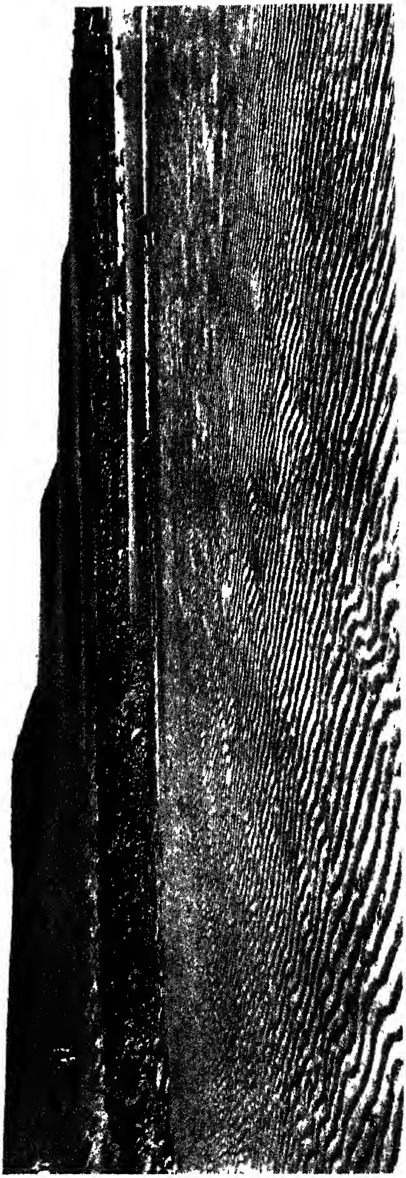
FIG. 131.—COARSE GRAVEL AND SHINGLE, SHOWING IMBRICATED STRUCTURE.

The arrow indicates the direction of the current.

There seems also to be little doubt that those tumultuous assemblages of hummocks, cones, and ridges known as kames, are of the nature of gravelly moraines, deposited in front of giant glaciers or district ice-sheets. Often associated with them are wide sheets of sand, loam, and clay, which spread out over the low-lying tracts, upon the borders of which the gravelly moraines have been accumulated. Perhaps one of the best areas for the study of these phenomena is the great valley of Strathmore.

Although the external form of glacial and fluvio-glacial deposits is often original, yet occasionally widespread sheets of sand, gravel, etc., have been so cut up by subsequent epigene action as to present a more or less rapidly undulating or corrugated surface. When this is the case, such a denuded plain now and then simulates the appearance of "drums" and "kames." Usually, however, the observer is not likely to mistake a surface of erosion for one of accumulation. If the deposits consist of evenly bedded gravel, sand, etc., the subsequent origin of the mounds and banks will be disclosed by the manner in which the horizontal beds are truncated by the slopes of the ground. It is more difficult to differentiate between a true "drum" or "drumlin"—that is, a bank or ridge of boulder-clay due to glacial accumulation—and banks of the same material which have resulted from the irregular erosion of a thick continuous sheet. If the banks do not trend in the same direction as the *roches moutonnées* and striæ of a district, then they are not true drumlins. Should their trend appear to coincide generally with that of glaciation, the whole modelling of the surface must be studied before we come to the conclusion that the banks are original structures. If they have been carved out of a sheet of boulder-clay by running water, evidence of this should be found in the arrangement of the intervening hollows, which will be grouped much in the same way as the feeders and tributaries of a stream. In other words, the banks and ridges of the district will not be arranged throughout in parallel positions, but will fan-out as they are followed in a direction opposite to that of the water-flow. Moreover, the existing brooks and their feeders, or, should these have disappeared, the evidence of their former presence afforded by flats and terraces of alluvial deposits occupying the hollows, would be sufficient to convince us that the banks or ridges were not true drumlins but secondary structures. It is to be noted, however, that true drumlins are of two kinds; while some have been accumulated as such underneath the old ice-sheets, others would appear to be merely

PLATE LXIV



RAISED BEACHES, NEAR ELIE, FIFE.

Photo by A. G. Stenhouse.

[*To face page* 309

the remnants of widespread sheets of boulder-clay which have been exposed to subsequent glacial erosion. In Galloway, for example, the low grounds extending outwards from the mountains were originally deeply covered with extensive sheets of boulder-clay, by the *mer de glace* that formerly overflowed all that region. Long after the disappearance of that ice-sheet, great glaciers streamed out from the mountain-valleys for some little distance and trenched and furrowed the older boulder-clay, thus forming a series of secondary drumlins.

RAISED BEACHES. These are flats and terraces occurring at various levels above the sea (see Plate LXIV.). They may consist of ordinary beach materials—gravel and sand with rolled and broken sea-shells, etc. Along the margins of estuaries they often form wide flats, composed for the most part of finer materials—sand, clay, loam, silt, etc. On our more exposed sea-coasts the raised beach-lines are frequently mere platforms and ledges, which have been sawn out of the solid rocks by the sea. Many old beaches are backed by cliffs, at the base of which sea-worn caves not infrequently appear. In Scotland there are three " ancient sea-margins " which are particularly noteworthy. They occur at heights of 100 feet, 50 feet, and 25 feet respectively. The highest is the oldest, and is best developed in the basins of the Forth, the Clyde, and the Tay. It is composed largely of laminated brick-clay, together with fine sand. Scattered through these deposits occasional stones occur, and now and again large erratics are even common. The beds not infrequently yield Arctic species of shells, etc. The observer will find it interesting to follow the 100 feet beach or terrace up the valleys until it merges into terraces of ordinary fluviatile shingle and gravel. When the latter are traced farther inland into the mountains, they will eventually be found to interosculate with fluvio-glacial gravels and terminal moraines.

The two lower terraces are of later date; but their geological history has not yet been so fully worked out as it deserves to be.

LACUSTRINE AND FLUVIATILE DEPOSITS. The sites of old lakes are readily detected. They invariably occur, as might have been expected, in hollows and depressions, and usually form level meadow-lands. Their margins, as a rule, are well defined. The observer should never miss the opportunity of examining any cuttings in which the old lacustrine deposits are exposed. Very often the immediate surface is occupied by peat of less or greater thickness—or several layers of peat may be interstratified with sand or silt. The peat may consist entirely of plants which still grow in the neighbourhood. Now and again, however, Arctic plants have been detected in the basal part of the peat or in the immediately underlying silt or clay. Sometimes, also, traces of Arctic animal life are met with in the same deposits. This proves that some of these ancient lakes date back to the glacial period. Even those lacustrine deposits which are entirely of post-glacial age, have often yielded interesting fossils—amongst which may be mentioned remains of the ancient types of oxen (*Bos primigenius*, *B. longifrons*), the great Irish deer, wolf, beaver, etc., not to mention relics of prehistoric man. Freshwater shells also frequently occur, forming beds of shell-marl.

Very few broad river-valleys fail to show old terraces of gravel, sand, etc., occurring at various levels above the present streams. These mark levels at which the rivers formerly flowed. Terraces of this kind are best developed in valleys which have been more or less abundantly clothed with glacial and fluvio-glacial deposits: or in regions where the rocks have yielded not less readily to fluviatile erosion. In a country like Scotland, where the rocks are all relatively "hard," old river-terraces may be said never to occur outside of preglacial valleys. So long as our rivers follow their preglacial courses, those terraces are almost invariably in evidence, the rivers making their way through broad open valleys. No sooner, however, does a stream leave its preglacial course to cut its way through the older rocks, than the whole character of the valley changes. The stream no longer flows through a wide terrace-fringed valley, but through a relatively narrow ravine.

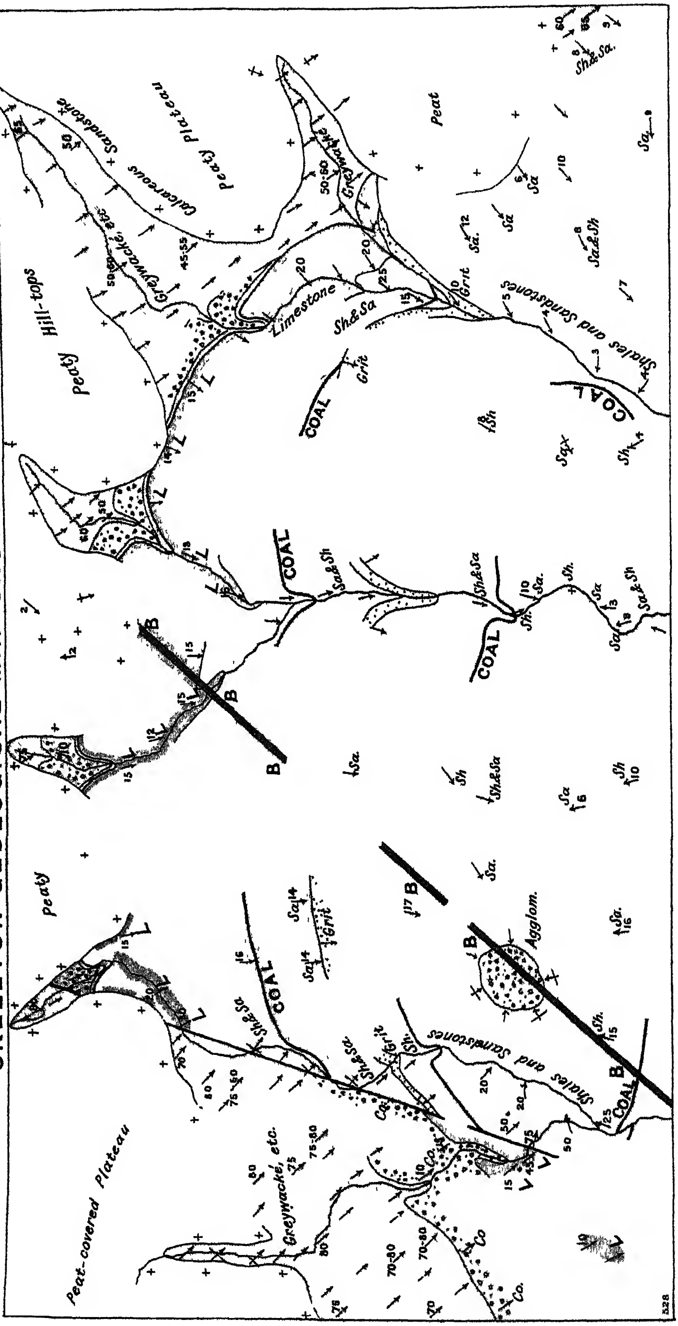
PEAT. Reference has been made to the occurrence of peat in old lacustrine depressions. But, as everyone knows, peat often covers wide areas of rolling low ground and high plateau, and even swathes relatively steep mountain slopes. In some regions, indeed, it is found capping flat hill-tops. There is no difficulty in mapping peat-bogs, but a careful study of their phenomena has still to be made. It is well known that many peat-bogs cover and conceal the stumps and stools of trees which are rooted in an ancient soil, and obviously, therefore, grew *in situ*. Not only so, but deep cuttings in certain peat-bogs have revealed the presence of one or more such old "forest-beds" occurring one above another in the peat itself. Scandinavian, Danish, and German observers have detected in the peat-bogs of Northern Europe similar phenomena, and have gathered much additional botanical evidence of varying climatic conditions. Until recently few attempts had been made by competent botanists to subject the peat-bogs of this country to a like careful examination. Geologists specially interested in the later chapters of the stony record have for a long time believed that a rich harvest of results would yet be reaped in this promising field of inquiry. The purely geological evidence seemed to lead to the conclusion that the peat-bogs, with their associated "forest-beds," belonged to a period during which several well-marked alternations of climate took place, the peat being the product of wet and cold conditions, while the "forest-beds" indicated relatively dry and temperate conditions. The results obtained by Dr F. J. Lewis, in his botanical investigations into the composition and structure of our peat-bogs, abundantly confirmed that conclusion. He discovered distinct zones of Arctic plants in the peat of Lowlands and Highlands alike, and thus we can no longer doubt that the closing stages of the geological history of our islands were characterised by alternations of cold and temperate climatic conditions.

CHAPTER XXI

GEOLOGICAL MAPS AND SECTIONS

Geological Maps and Explanatory Memoirs. Geological Sections—Horizontal or Profile Sections should show both the Form of the Ground and the Geological Structure; Direction in which such Sections should be drawn; Method of Plotting a Section on a True Scale. Vertical Sections. Surveying by Aerial Photography.

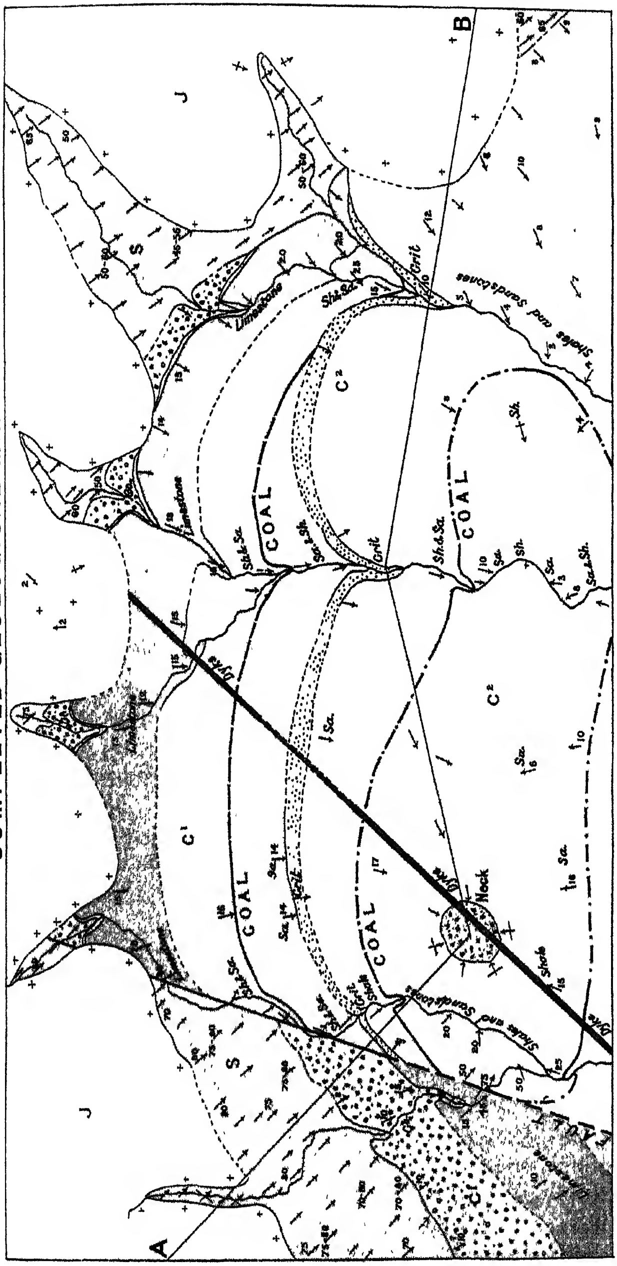
Geological Maps and Explanatory Memoirs.—The accompanying maps (Plates LXV., LXVI.) will serve to illustrate the method of tracing geological lines, some account of which has been given in the two preceding chapters. In Plate LXV. only the actual rock-exposures seen by the geologist are represented. These are indicated by the arrows and continuous lines, the patches of colour showing the extent of the areas where rocks come to the surface. Plate LXVI. represents the same region with the several boundary-lines, etc., completed. The direct and indirect evidence which guides the observer in carrying outcrops, faults, etc., from one point to another, must no doubt be of unequal value. In some places it may be so convincing that one may almost feel justified in representing outcrops, etc., by means of continuous lines, while in other places it may be so slight that the boundaries laid down upon the map can be only an approximation to the truth, and should, therefore, be indicated by dotted or interrupted lines. A glance at the maps will show that the geological structure of the region represented is so devoid of complexity, and the evidence so full, that the observer could hardly go far astray in carrying lines across such a country. The maps are merely diagrams, however, designed to bring into one view certain leading structures and the method of tracing these, and therefore it must not be inferred that outcrops can be always so satisfactorily followed. Sometimes, indeed, the ground-rocks are so obscured over wide areas, by superjacent glacial or alluvial accumulations, that the general geological structure can only be surmised, and the following of outcrops becomes impossible. At other



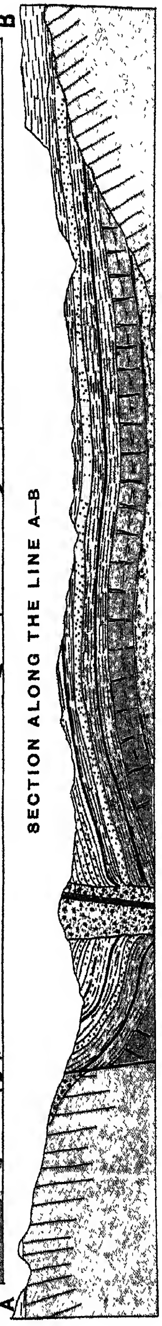
SKELETON GEOLOGICAL MAP SHOWING FIELD DATA

Peat-covered Plateau
Greywacke, etc.
peaty
Hill-tops
Calcareous Sandstone
peaty plateau
Greywacke
Limestone
Sh & Sa
Sa & Sh
COAL
Grit
Shales and Sandstones
Peat
Agglom.
Co.
Sh
Sa
B
L
V
528

COMPLETED GEOLOGICAL MAP


A
B
J
S
C¹
C²
COAL
Grit
Limestone
Dyke
Neck
Sh.&Sa.
Sa.&Sh.
Shales and Sandstones
Shale
Sa.
Sh.

SECTION ALONG THE LINE A—B



Between pages 312-313]

times the region may be so abundantly faulted that no cautious geologist would venture to continue an outcrop beyond the point where the rock itself could be proved to exist. Occasionally, however, in the case of valuable rocks and minerals (coal, ironstone, etc.), the observer, desirous of helping the mining engineer in his search for such seams, might be justified in indicating by means of interrupted lines the general course which he thought the outcrops were likely to take. But in doing so, he would be careful to note upon the map, or in his description that the outcrops were largely conjectural, and therefore not to be implicitly trusted.

Three geological systems are represented on the diagram-map—Silurian (S), Carboniferous (C), and Jurassic (J). Each of these systems, we shall suppose, has yielded to the investigator its assemblage of type-fossils. It will be observed, however, that, even in the absence of fossils, the geologist could have had no difficulty in detecting the presence of three distinct series of strata, and in ascertaining the order of their succession. The rock-exposures are so numerous that they at once reveal the geological structure. The series marked J, for example, rests with a strong unconformity upon the series C; the latter bearing in like manner a similar relation to the series S. Another unconformity of less importance occurs in the Carboniferous series, where the upper group (C^2) is represented as gradually stealing across the outcrops of the lower group (C^1)—the structure, indeed, is a combination of overlap and unconformity. The accompanying section is taken along the line A—B and gives a view of the general geological structure.

In his monograph or explanatory memoir of such a region, the geologist would probably begin by sketching its physical features, after which he would proceed to give some account of the general distribution of the several systems and their relation to one another. Next would follow a particular description of each, beginning with the oldest. The several faults and the eruptive rocks would likewise call for ample notice. In short, every detail of scientific interest and economic importance would be duly set forth in its proper place. But if his monograph were written for experts only, the geologist would necessarily leave much unsaid, knowing that his readers might be relied upon to fill in outlines and to draw obvious inferences for themselves. He might, indeed, not infrequently content himself with a bare narration of facts, and leave these and his map to tell their own tale. Interpretations and explanations would only be called for in cases where the evidence was incomplete or not quite clear.

The beginner, however, who essays to work out the geological structure of a district, would do well to ponder over the evidence as it grows, and endeavour to realise the particular conditions under which the various rocks and rock-structures originated. His object is not only to make a correct geological map and to present a detailed report of what he has observed, but to picture to himself as clearly as he can the succession of changes which have taken place in the region surveyed. If he is dealing with sedimentary strata, he must be on the alert to notice every variation in the character of the deposits, every fact that would seem to throw light upon the conditions that obtained at the time the strata were being accumulated. As the evidence furnished by fossils is always most important, he will be on the constant outlook for these. Only by keeping each kind of evidence—that of the fossils and that of the rocks themselves—constantly in view, can we hope to read geological history aright. If we have previously made ourselves well acquainted with the nature and mode of formation of sediments now being laid down in lakes, estuaries, and seas, and have acquired a sufficient knowledge of the various ways in which organic remains come to be entombed, we shall be prepared to give a good account of any series of sedimentary strata we may encounter. Most of the fossils we may detect will in all likelihood belong to well-known genera—probably most of the species themselves will already have been recognised by palæontologists—so that with the combined evidence of rocks and fossils the observer will be in a position to realise the conditions under which the fossil-bearing beds were laid down. He should be able, in short, to summon up a picture of the past. The more fully he has stored his mind with a knowledge of geological changes now in operation, and the more consistently he applies this knowledge towards the interpretation of the stony record, the better investigator must he become, and the more clearly and vividly will the dead past live again for him. It is this clothing of the dry bones with flesh, this reconstruction of long-vanished lands and seas, this repeopling of the world with types of life that have passed away for ever, this gradual unfolding of earth-history—it is this, perhaps more than all else, that fascinates the earnest student of geology. The "scientific imagination," therefore, ought from the first to be stimulated by every observation one makes. Even within the limits of a single quarry one may often meet with evidence from which to reconstruct quite a number of interesting geological episodes. Small and unimportant the phenomena may seem to be, but the care bestowed on their interpretation will not be lost. Gradually, as we continue our investigations, our eyesight becomes sharpened; we not only see better than we did when we commenced, but are able eventually to take a wider outlook, and to piece together bits of evidence which at first might have appeared isolated and unconnected. From all which it is obvious that the observer who cultivates the scientific imagination is likely to produce a better and more reliable geological map than the cartographer who declines to look beyond the obvious facts. The former is on the way to become a shrewd generaliser and discoverer; the most the latter can hope to do is to provide materials for others with a wider outlook to work up and interpret.

Geological Sections.—When the geologist has completed his map, he usually prepares one or more horizontal or profile sections to illustrate the general structure of the region. With an accurately constructed map, sections might often be dispensed with, since anyone who could read such a map could draw sections across it in any direction. Few maps, however, are large enough to show all the needful data, and the smaller and more generalised the map is, the more necessary do explanatory sections become. Two kinds of sections are constructed, namely, *Horizontal* or *Profile* and *Vertical*, the former being designed to show the form of the ground and the geological structure of the region traversed, while the latter are meant to exhibit in detail merely the vertical succession of the strata.

Horizontal (Profile) Sections. If these are to be accurately constructed, they must be drawn upon a true scale—that is, the vertical and horizontal scales must be the same. The young geologist's first attempts at section drawing should therefore be on this true or natural scale. If the vertical scale be exaggerated, it is obvious that the lines which are meant to show the geological structure must be correspondingly distorted. A glance at the two sections (Figs. 132, 133) will serve to make this plain. Fig. 132 is drawn on a natural scale, and therefore exhibits the actual form of the surface and the true dip of the strata. In Fig. 133 we have the same section; but in this the vertical is three times greater than the horizontal scale, the result being that not only are the surface-features grossly exaggerated but the geological structure is distorted, the inclination of the strata being greatly in excess of the true angle of dip. It is only by carefully plotting our sections to exhibit the actual form of the ground, that we learn to appreciate the intimate relation that obtains between surface-features and geological structure. Everyone is prone to exaggerate slopes—even experienced artists frequently do so, especially in the case of mountains—and the young geologist who neglects to train his eye by frequent section drawing on a true scale, is not likely to escape this common failing. The beginner will find it excellent practice to draw topographical (not geological) sections in all directions across some of the hilly tracts represented on the large 6-inch maps of Scotland. He will doubtless be surprised to see how inconspicuous many heights appear when drawn to scale, how relatively gentle are the undulations of the surface even in a mountainous tract. In the same way he will recognise that the deep basins occupied

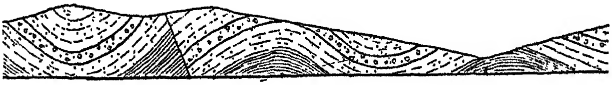


FIG. 132.—SECTION ON A TRUE SCALE, THE HORIZONTAL AND VERTICAL SCALES BEING THE SAME.

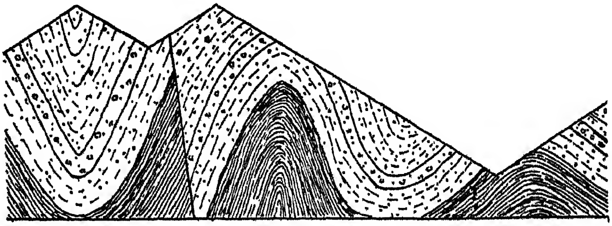


FIG. 133.—SECTION ACROSS SAME AREA AS IN FIG. 132, THE VERTICAL BEING THREE TIMES GREATER THAN THE HORIZONTAL SCALE.

PLATE LXVII

LOCHAN AN IASGAICH, ROSS-SHIRE. [Showing in middle distance numerous hummocky moraines.]

Photo by H.M. Geological Survey.

[*To face page* 316

by our larger lakes when seen in their true proportions are mere shallow pans or troughs. Loch Ness, for example, is 780 feet deep, but then it is not less than 22½ miles long, so that the length is 152 times greater than the depth.

Of course it is not always possible to plot geological sections on a true scale. If the region to be illustrated be of great extent, say 100 miles across, it is obvious that we must generalise both the topography and the geology. Even in such cases, however, it is important to indicate as clearly as may be the leading surface-features of the region and the relation of these to the geological structure. A similar remark holds good with regard to all sketch-sections. Should the heights and slopes of the land be so inconspicuous as to be barely perceptible when drawn upon a natural scale, it is often necessary to exaggerate them in order to show their relation to the internal structure. The exaggeration, however, should not be so pronounced as to amount to positive distortion.

In running a geological section, care should be taken to draw it as nearly as possible at right angles to the strike. If the strata be inclined in the same direction throughout a district, the section will necessarily follow a straight line. But should the strike vary from point to point, the line of section will be correspondingly sinuous or zig-zag. Reference to Plate LXVI. will show how frequently the direction of a section-line must change, when it is desired to bring into one connected view the general geological structure of a whole district. The section in question is a mere diagram, and is therefore not drawn to scale, but it exhibits the leading surface-features and their relation to the underground structure.

There is no difficulty in plotting a profile-section on a true scale. If the student has laid down his geological lines upon the 6-inch map of the Ordnance Survey, all he has to do is first to draw a line across the map in the direction to be followed by his section. Next, on a separate sheet of paper, he draws a line to represent the sea-level. Upon this datum-line he erects verticals for the heights of the land traversed by his section, which he obtains, of course, from the contours on the map. When the extremities of these lines are connected they give the average form of the ground. If it be desirable to reproduce the surface-features in greater detail, the observer may walk over the ground with his section in his hand, and so modify the line as to show the subordinate irregularities that appear between the measured contours. Usually, however, this refinement is not necessary, when the contour lines upon the map succeed each other at intervals of 100 feet or less. At the higher elevations of the land the intervals between the contour-lines increase to as much as 250 feet; and when such is the case the geologist will probably consider it advisable to revisit the ground in order to make the upper line of his section represent, as closely as may be, the varying configuration of the surface.

Having satisfied himself as to the correctness of this upper line, he then proceeds to insert the dips of the strata, and every detail shown upon his map along the line of section. Probably the section will now and again traverse places where outcrops are not seen, but, the structure of the ground having been carefully worked out, he will usually have no difficulty in filling in these blanks from the evidence supplied by rock-exposures seen elsewhere on the same geological horizon. After all the data referred to have been inserted, the question arises—how far are the dips exposed at the surface to be continued downwards? The depth to which we may carry our lines will naturally depend upon the geological structure. If our section should traverse normal anticlines and synclines, we need have no doubt as to the conduct of the lines below the surface. In the case shown in Fig. 134 the strata between *a* and *b* are obviously symmetrically folded. We therefore should be justified in continuing the dips of the synclinal strata downwards for some distance at the same angle as they show at the surface, and then gradually cause the degree of inclination to diminish

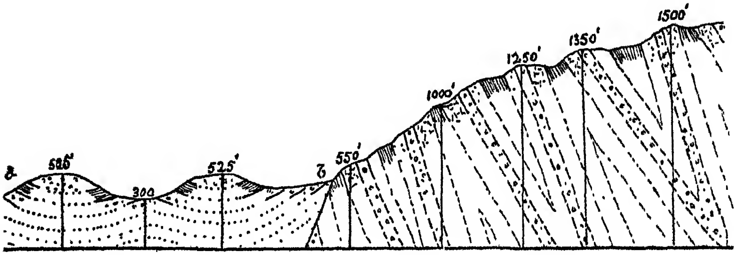


FIG. 134.—DIAGRAM-SECTION.

Vertical lines = heights above datum-line (*d*). Continuous lines = outcrops. Interrupted and dotted lines = inferred direction of strata below the surface.

until the beds should become horizontal in the core of the synclinal trough. If the rock-folds, instead of being "open" as shown in the diagram at *a*, were closely compressed as between *b* and *c*, the curves of synclinal and anticlinal cores would be more or less sharply angular; and in our section we should have to continue the limbs of a syncline downwards for a relatively greater distance before the trough core was reached. In short, when gently inclined strata dip towards each other at approximately the same angle, we may be sure that the inclination of the limbs will rapidly lessen as they reach the trough core, while in the case of steeply inclined and closely compressed inclined folds, the limbs of a syncline must descend to a relatively greater depth before they meet.

In regions which have not been topographically surveyed, or the maps of which, if such exist, give very few elevations, the geologist must of course do his own levelling, if he desires to plot a section on a true scale. In such a case he may select any line for the base of his section—either the sea-level, the surface of some lake, or the bottom of some valley, etc., or he may prefer to erect his section on some imaginary line drawn at any distance below the surface.

Vertical Sections. These are sections so drawn as to show all the strata piled up, as it were, in a tall column in their proper order of succession. Where no unconformities occur, the dip of the strata is usually neglected and the beds are arranged in a horizontal position. As sections of this kind are meant to show in detail the succession of the strata in a coal-field or other area containing beds and seams of economic importance, they are drawn on a large scale—a much larger scale than would be employed in the construction of even the most elaborate profile section. In the case of vertical sections great accuracy is required, the thickness of each individual bed being carefully measured in exposed rock-sections, or obtained from other reliable sources, as from records of the rocks passed through in sinking wells, pits, bore-holes, etc. The Geological Survey publishes sheets of such sections to show the succession of beds encountered in our coalfields. By comparing the vertical sections illustrating any particular coalfield, we can see at a glance how the same series of strata varies as it passes from one part of the coalfield to another. Similar vertical sections, usually on a much smaller scale, are now and again constructed by geologists for the purpose of comparing the succession of strata met with in one place with that encountered in some other area where rocks of the same age occur. It is, in short, a graphic method of showing how the same formations and systems vary in character as they pass from one region to another.

Surveying by Aerial Photography.—The construction of geological maps according to the methods described in the foregoing pages involves very laborious work and demands a high degree of skill and a wide knowledge of rocks in the field on the part of the geologist. When the surface evidence is supplemented, as is usually the case, from records obtained from excavations, bore journals and mines, the resulting map forms a source of valuable information both for scientific and economic purposes. Where speed is essential, or where the area to be surveyed presents special difficulties, a survey, essentially topographical, by aerial photography is useful. Many archæological and geological features are more easily seen from the air than on the ground. As geological structure controls topography it follows that an outline of the geology of a district may be attained more rapidly by aerial photography than by any other means. The instruments used, the methods employed and the special difficulties to be met are dealt with in the works referred to below.

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CHAPTER XXII

ECONOMIC ASPECTS OF GEOLOGICAL STRUCTURE

The Search for Coal—Conditions under which Coal occurs. Trial Borings. The Search for Ores—General Considerations which should guide the Prospector; Nature of the Evidence. Prospecting by Geophysical Methods. Geological Structure and Engineering Operations—Excavations, Tunnels, Foundations.

IN preceding chapters dealing with Tectonic or Structural Geology, much that is of interest and importance to engineers and others has been set forth in more or less detail. No attempt, however, has been made to indicate the various ways in which a knowledge of rock-structures may be utilised by mining and civil engineers, architects, and others—for the simple reason that the application of the knowledge in question must be sufficiently evident. In the present chapter, however, it may not be out of place to give a few supplementary notes which could not be well inserted in earlier pages.

The Search for Coal.—In regions the geological structure of which is well known, and good maps of which are available, not much difficulty need be experienced by the mining engineer who can read and interpret geological maps and sections. He may often be at a loss, however, in searching for coal, etc., in a country the geology of which is only imperfectly understood, or even not known. Under such conditions his first care would necessarily be to ascertain the geological age of the sedimentary strata by searching for fossils. Coal occurs in several geological systems. In Britain, workable seams are practically confined to the Carboniferous system, and the same is largely the case in many other regions, both in Europe and North America. In Australia, India, and Southern Africa, and in Virginia and North Carolina, U.S.A., workable coal occurs on higher geological horizons—namely, in late Palæozoic and early Mesozoic strata. Here and there, but only at wide intervals, seams of economic value are also encountered in the younger

Mesozoic Systems (Jurassic and Cretaceous). The Cainozoic strata in several regions yield lignite or brown coal, as in North Germany, Italy, and Washington, U.S.A., or very rarely steam coal, as in Spitsbergen. The mining engineer who may be on the outlook for coal will do his best, therefore, to discover fossils—the presence of which will determine the geological horizon of the strata. Should the fossils prove the strata to belong to an older period than the Carboniferous, workable coals are not likely to be met with. Hopes, however, may be encouraged should the rocks prove to be of Carboniferous or later age. In such a case the engineer would endeavour to ascertain the general character of the strata. Should thick marine limestones be present in the series, and the accompanying shales and sandstones yield only brachiopods, cephalopods, and other types of marine life, and should few or no traces of land-plants occur, then there would be little probability of discovering workable coal-seams. Should the strata, on the other hand, consist of rapidly alternating beds of sandstone and black or dark-coloured shale with occasional seams of clay, and layers of clay-ironstone, such a succession might be considered hopeful. The appearance here and there of thin limestones of marine origin would not necessarily be an adverse sign, for coals and limestones are well known to occur, now and again, in one and the same group of strata. But should the constantly recurring beds of shale contain plant-remains, often very well preserved, while the sandstones showed streaks and thin lenticular layers of coaly matter, and the clays were charged with rootlets, our hopes of encountering coal would be greatly increased. It must be remembered, however, that the occurrence of black shales is not of itself a sure indication of the presence of coal in any series of strata. In almost all geological systems, particularly in some of the older Palæozoic formations, black shales may occur without the accompaniment of even the most exiguous seam of coal. Let us suppose, however, that our engineer has encountered a succession of strata closely resembling those which in other parts of the world have yielded coal-seams. He naturally examines carefully every rock-section in the hope of discovering outcrops of the fossil fuel. This hope, however, might not be realised, for, owing to weathering, sections are often rendered more or less obscure, and outcrops of readily yielding beds are frequently concealed under sheets of débris. Search in the alluvial deposits of the valleys, however, might be rewarded by the discovery of fragments of coal, and the source of these would be tracked up-stream in the usual way (see p. 283). Were the region not thickly covered with superficial accumulations, outcrops of coal might be expected to betray their presence by the blackened soils and subsoils resting upon them.

Having satisfied himself as to the presence of coal, the engineer would proceed to open up any outcrop, so as to ascertain the thickness and quality of the seam, and the nature of the "roof" and "floor." Should the coal be too thin or too poor in quality to pay the cost of working, we should not necessarily give up all hope. The engineer would probably suggest that before abandoning the search the ground should be proved by putting down one or more bore-holes. Before any such attempt is made, however, the geological structure of the area ought to be worked out, the character of the strata most carefully noted, and some reasonably clear notion formed as to the conditions under which the strata have been accumulated. It may be that the coals are persistent at definite horizons throughout the whole area, or, on the other hand, they may be merely lenticular seams of no great extent, and occurring at irregular intervals. In the former case, it is obvious that a valuable coalfield would be waiting development, while in the latter case the chances of striking a workable seam might be too uncertain to attract the attention of capitalists. Careful investigation of the exposed sections should enable the observer to decide the question. Some coals consist of plant material which has been drifted to the sites where the coal is now found and may rest upon any kind of substratum; such coals, moreover, tend to be impure, variable in thickness, lenticular in mode of development, and of limited lateral extent. Most good coal-seams, however, rest upon an underclay crowded with rootlets and represent growth *in situ*. (See also p. 77.)

Although the observer may have assured himself that only thin coals crop out at the surface, he need not, on that account, conclude that further research is useless. It is quite possible that the seams seen in actual section may thicken-out as they are followed downwards. But if the strata are undulating and the same beds come again and again to the surface—each recurring coal-seam continuing thin and unimportant—he will have good reason to infer that the series is not worth further investigation. Should the rocks, however, be partially concealed by overlaps or unconformities or by faulting, or otherwise not be accessible owing, perhaps, to thick coverings of surface accumulations, or to the paucity of sections, the observer would not be wise to abandon his search. The occurrence of thin seams of coal, or even the mere presence of numerous plant-remains such as are commonly associated with coal-bearing strata, taken in connection with the obviously shallow-water origin of the strata and the absence of any evidence of deep-sea or purely marine conditions, would be sufficient to justify trial-boring. The frequent occurrence of rootlet-beds, with or without overlying coal-seams, would suggest the probability that the unexplored parts of the series might contain more or less persistent beds of coal. The absence of rootlet-beds, however, would not be quite so favourable a sign. It would lead to the inference that any workable coal-seams that might occur would be apt to be somewhat inconstant—lenticular sheets, thickening and thinning irregularly. But, inasmuch as seams of this character not infrequently attain a very considerable thickness and extend over wide areas, it would obviously be important to ascertain the direction in which thickening was likely to take place, and thereafter to test the ground by borings.

The Search for Ores.—Bedded ores occur under the same conditions as any other sedimentary rock, and are therefore to be sought for and traced by the ordinary methods employed in field geology. The same to a large extent is true of lodes and irregular ore-formations of all kinds, but the search for these is not, as a rule, so easy. Perhaps most discoveries of such ore-deposits have been the result of accident. A large number, however, must be credited to those sanguine and often admirable observers, known as "prospectors," the most successful of whom have, wittingly or unwittingly, usually followed geological methods of research. Having become familiar with the ore-formations of some particular region, and learned to recognise the manifold appearances presented by them at the surface, such as the coloration of soils and subsoils, the character of the gossans, etc., a prospector could hardly fail of success so long as his researches were confined within the same geological area. Should the same observer, however, essay to prospect in a totally different region, he might often be nonplussed. In point of fact, many mining men have wasted time and substance in exploring wide tracts of country which a knowledge of geology might have led them to avoid, as probably barren ground; while, on the other hand, such knowledge might have directed their attention to areas in which prospecting was likely to lead to successful results.

Lodes and irregular ore-formations may occur in almost any kind of rock, and are not restricted to a particular geological horizon, for they are met with in Palæozoic, Mesozoic, and Cainozoic rocks alike. But although this is true, yet by far the larger number of such formations are associated with the older geological systems. It is exceptional to meet with valuable lodes, etc., in Cainozoic and even in Mesozoic rocks, except in the vicinity of eruptive masses. Most lodes, etc., are of more or less deep-seated origin, and are thus least likely to be met with traversing rocks of relatively late geological age. They are, therefore, to be sought for in the more ancient rocks, because these have experienced vast denudation, their present surface in many cases being several thousand feet or yards below that which existed at the time the lodes were being filled. It must not be supposed, however, that every region of highly denuded ancient rocks is likely to contain valuable ore-formations. We know, in fact, that such is not the case; but certainly it is to such regions that the prospector ought to turn his attention. The more highly folded, fractured, and dislocated the rocks are, the better from his point of view, while the presence of batholiths, sills, and dykes of eruptive rock would be rather a hopeful sign, as will be gathered from what has been set forth in Chapters XVI. and XVII. as to the mode of occurrence and origin of ore-formations.

Let us suppose, therefore, that an explorer has entered a sorely denuded hilly or mountainous region of ancient rocks, the general character and geological structure of which seem favourable. It is obvious that he must be guided in his investigations by the principles already illustrated in connection with geological map-making. He must be on the outlook for every indication that may lead him to the hidden treasure. Any marked change in the form of the ground will be noted, such as a prominent narrow ridge running in a linear direction, or a like well-marked hollow. The former may mark the outcrop of a lode of harder consistency than the rocks it traverses, while the latter may indicate the back of a vein filled with less resistant mineral matter. Even when the outcrop of a lode produces no marked surface feature, it will yet, in many cases, betray its presence by more or less pronounced coloration of the soil. This is due, of course, to the decomposition of the minerals occurring in the vein. Very frequently the overlying soil will be stained red or yellow, owing to the presence of iron-oxides, which are of common occurrence in most gossans. Other minerals, if sufficiently abundant, will indicate their presence by various tints or hues. Green colours, for example, are yielded by ores of copper, nickel, or chromium ; commingled blue, green, and red stainings are yielded by copper ores ; lead-ore is often indicated by yellow and green stainings ; manganese-ores are black, while auriferous quartz is often rusty and cellular from the removal of pyrites. Again, a lode may be indicated by springs coming to the surface along a definite line, for lodes often act as subterranean dams ponding back the water that descends towards them along the various division-planes of rocks, and forcing it to the surface. Such springs not infrequently contain much mineral matter in solution, and may give rise to superficial accumulations of tufa, limonite, etc. Should the water contain deleterious ingredients (derived, for example, from the decomposition of iron pyrite), it will naturally produce a more or less striking effect upon the vegetation. A pyritous lode is, in this way, sometimes indicated by the poverty-stricken character of the vegetation in its immediate neighbourhood, which may be in strong contrast with that covering the country-rock.

Fragments of veinstone and ore occurring in a water-course will naturally be suggestive, and should the fine gravel and sand of the stream contain grains and particles of gold or other valuable mineral, the prospector—always a sanguine man—will feel confident of success. Stopping ever and anon, as he proceeds up-stream, to examine the contents of the alluvial deposits, he may at last reach a point above which no fragments or particles of metal or ore can be found. Searching the adjacent valley-slopes, the observer discovers perhaps scattered fragments of veinstone and possibly ore. But whether these do or do not occur, the prospector would certainly be justified in digging pits or trenches down to the solid rock, in hopes of striking the ore-formation itself. While the search for such formations is, for obvious reasons, most promising in valleys, yet the land-surface separating one valley from another—more especially if it be a hilly region—must not be neglected. For, owing to long-continued weathering, such surfaces are often sprinkled in places with angular fragments, or partly mantled by sheets of rock-rubbish. Should lodes traverse such a tract, they are almost sure to be betrayed, even in the absence of conspicuous outcrops, by the presence of loose fragments, or *shode-stones*, as they are termed by Cornish miners. By the careful tracking of these stones their source may be located. It need hardly be added that the prospector who has a good working knowledge of ores, and is quick to understand leading geological structures, is more likely to succeed than the geologist who, however expert he may be in unravelling and interpreting rock-structure, is yet unfamiliar with the various "indications" that reveal so much to a keen-eyed mining man. The latter, however, whose experience may have been gained in some limited region, is often at a disadvantage when he begins prospecting in a new country. Not infrequently he is possessed with the belief that the mining region in which he was brought up must be the type of all others. If the only valuable lodes of that region have a north and south direction, he expects that the same is likely to hold good elsewhere, no matter what the geological structure of the ground may be. He often makes similar assumptions as to the gossans. The auriferous reefs of the country he has left may crop out as ridges of ferruginous cellular quartz, and when similar gossans are encountered in a totally different area, he is apt to jump to the conclusion that these also must be gold-bearing, although not a trace of gold may occur either in the gossans or the veins they cover. Experience has shown, therefore, that it is never safe to infer that the appearances presented by the shode-stones and gossans of one region must necessarily be characteristic of mineral regions elsewhere. They may or may not be, but only by careful examination of the gossans and the unaltered veins below can doubt be set aside.

Although lodes and irregular ore-formations occur more commonly in association with the older geological systems, yet under certain conditions Mesozoic and even Cainozoic rocks have become charged with valuable ores. The most important ore-bodies of this late age are met with in the vicinity of massive igneous rocks in volcanic regions which have experienced much erosion. The ores in question frequently appear as contact-formations (particularly in andesites and rhyolites), and the prospector, therefore, should do his utmost to trace the line of junction between such an intrusive mass and the rocks it traverses. Should the effects of solfataric action be manifest, this will be so far a favourable sign, since it is just under these conditions that fissures and faults have in many cases been filled with ores and other minerals, and the adjacent "country-rock" has been impregnated. Now and again, however, the observer finds that denudation has not yet laid bare the intrusive masses from which heated solutions have been derived; they still lie more or less deeply buried underneath the strata which have been affected by them. Their presence is suggested, in the first place, by the changes which these rocks have undergone. The latter are often much disturbed, shattered, and brecciated, and frequently highly silicified, shales being converted into hard siliceous porcellanite, and limestones into quartzose marbles, while feldspathic rocks are usually kaolinised. Moreover, dykes of quartz-porphyry, etc., are often more or less plentifully present. Native gold and various ores of silver, antimony, mercury, arsenic, etc., frequently impregnate and are disseminated through the silicified rocks under such conditions. The great volcanic tracts bordering the Pacific in North and South America, and the corresponding volcanic regions of Japan and other islands on the opposite side of that ocean, are in places notable for their ore-formations, many of which are of late Mesozoic and Cainozoic age.

Prospecting by Geophysical Methods.—In recent years the instruments and methods of the geophysicist have been adapted and applied to the solution of geological problems. These methods, when used along with geological observations and experience, have been specially helpful in cases where the solid rocks are concealed under superficial deposits. It has been found possible to locate ore-bodies, salt domes, etc., and to delineate the course of faults and the trend of important folds on ground where no surface evidence of their presence is available to the geologist. The chief methods employed may be classified as magnetic, electrical, gravitational, and seismic.

Details of the instruments and methods used will be found in the literature listed at the end of this chapter.

Geological Structure and Engineering Operations: Excavations.—In the construction of roads, railways, and canals, the nature of the rocks to be excavated must be ascertained before any estimate can be formed of the probable cost of an undertaking. Where the rocks themselves are not exposed to view, the engineer usually digs pits or puts down shallow bore-holes, and bases his estimate on the information thus obtained. The evidence is often quite sufficient for his purpose; at other times, however, it is inadequate, and may even be misleading. In the case of deep excavations and in the driving of tunnels, for example, something more than a mere knowledge of the rock immediately underlying the subsoil is required. Before undertakings of that kind are entered upon, the engineer ought to make a thorough examination of the geological structure, for the nature and character of the rocks at the surface may afford no indication of the nature of the rocks and rock-structures to be encountered at a short distance below.

In all such engineering operations it is most important to ascertain (*a*) the lithological character of the rocks to be penetrated, and (*b*) the mode of their arrangement or, in short, the geological structure. It is obvious that the actual cost of excavating will depend, in the first place, on the relative hardness of the rocks and the ease with which they can be extracted, which will often be determined by the nature of the jointing. The engineer has further to consider whether the rocks, when cut through, are likely to be self-supporting and of sufficient durability to withstand the action of the weather. Here the question of geological structures comes in, for it is obvious that a rock exposed in vertical section may be sufficiently durable if it be horizontally bedded, but quite untrustworthy if it be inclined in the wrong direction. The behaviour of the rocks with regard to the circulation of underground water has also to be taken into account. A highly permeable rock exposed in section may "weep" so copiously through pores or joints, that it is readily broken up when exposed to the atmosphere.

As it is hardly possible for the engineer to consider the lithological character of rocks apart from their geological structure, we may briefly indicate how strata may be expected to behave in cuttings according as they occupy horizontal or inclined positions.

When homogeneous firm rocks which show very few joints are horizontally disposed, they may usually be relied upon to be self-sustaining and to stand with approximately vertical faces in any open cutting. Such rocks are permeable only to a limited extent, and throw out little or no water. Hence, even when they occur as a series of thick beds separated by intervening layers of impermeable shales or clay, springs are of infrequent occurrence. Where the rocks to be cut through consist, on the other hand, of a series of highly porous and jointed beds with intervening impermeable shales, etc., springs and seepage may be expected. Even should water not filter through into the cutting, it is obvious that beds of such varying character are sure to weather unequally—the softer rocks will crumble away, and constant undermining of the overlying beds must take place. Under such conditions it becomes necessary to bench back the cutting, or to slope it until the angle of repose is reached. But where much water is discharged, the engineer may be compelled to mask the cutting with impervious masonry, apertures being left in the wall here and there to allow the water to escape.

When the strata are excavated in the direction of their dip, they can easily be treated as if they were horizontally bedded. The point of most importance is the nature of the rocks themselves. If the beds are firm and relatively impermeable, they may be expected to stand with vertical or nearly vertical faces. The chief dangers to be guarded against are the escape of water and the action of frost.

Cuttings made in the direction of the strike usually require different treatment. On one side of such an excavation the beds dip away from the line of cutting, and therefore occupy a strong position. Even should they consist of a series of alternating porous and impermeable rocks, they will often stand with a vertical face. The reason is obvious, for any water the porous beds may contain will tend to escape downwards along the planes of bedding; it is drained away from the cutting. On the opposite side of the excavation, the strata dip into the cutting and therefore occupy an unstable position. The tendency is for the truncated beds to slide downward; and should they consist of alternating pervious and impervious beds springs will come out, undermining will take place, and piecemeal or wholesale collapse must result. Rocks occupying such a position must be built up, care being taken to allow passage for the percolating water.

Excavations in massive igneous rocks will often stand with vertical or approximately vertical faces. The character of the jointing, however, has to be carefully considered, and the possible action of springs, in undermining and dislodging masses, and the general effect of frost, must not be overlooked. Schistose rocks, in like manner, are often firm and stable when opened up, more especially if the excavation runs in the same direction as the dip of the foliation. But when the cutting traverses such rocks along the strike, they are apt to behave much in the same way as sedimentary strata—on one side of the excavation they may be expected to stand well; on the opposite side slips and falls are likely to take place. Their stability, moreover, is often affected by the very irregular jointing, and by the variable character of the rocks themselves; so that while some schists readily allow the passage of water, others are more or less impermeable. The stability of this class of rocks further depends, to some extent, upon the nature of the foliation. Evenly foliated rocks, which simulate ordinary sedimentary strata, may be expected to behave much in the same way as the latter. When schists are much crumpled and contorted, however, the individual folia are more securely locked together, and slipping is much less likely to take place, so that such rocks may often be treated as if they were highly jointed igneous masses. Slates, it need hardly be said, more closely resemble steeply bedded sedimentary rocks, such as greywackés and shales, the stability of the faces of a cutting depending upon the direction of the planes of cleavage. Should the latter be traversed at right angles, the rock on both sides of the cutting will stand with vertical faces. When an excavation, however, is carried in the same direction as the strike of the cleavage, the rock will necessarily be more stable on one side than the other. In a word, the superinduced cleavage-structure plays the part of lamination and bedding in the case of sedimentary strata.

It is not necessary to add more than a word as to excavations in incoherent and non-consolidated rocks. Rocks of this kind will not stand with a vertical face, except in rainless or all but rainless regions. Under ordinary conditions, therefore, the engineer, in excavating soft, incoherent masses or beds, has to consider the slopes he must give to the sides of the cutting, for the angle of repose varies directly as the nature of the materials. Even in such cases it will usually be found that geological structure has its influence. Should the incoherent beds have a dip and be traversed at right angles to their inclination, they will almost invariably stand better on one side of a cutting than the other. Any water that may permeate the beds will tend to come out rather on the "weak" than on the "strong" side; slipping will be apt to take place from time to time on the former, but not so readily on the latter.

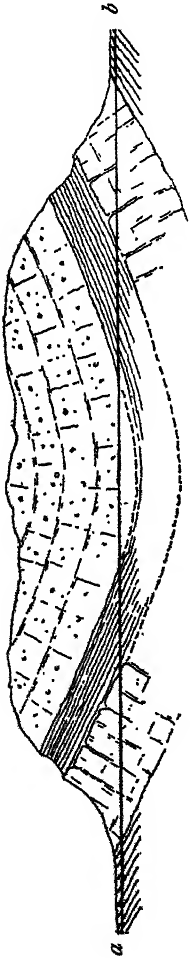

Fig. 135.—Tunnel through Synclinal Strata.

Tunnels.—If it be unwise on the part of an engineer to undertake important excavations or open cuttings without having previously examined the geological structure of the ground to be traversed, he would be deserving of censure if, before driving an important tunnel, he did not first endeavour to ascertain every fact connected with the rocks and their arrangement. In the case of horizontally bedded strata, not much difficulty would arise; the tunnel would be driven practically along the planes of bedding, and the character of the rock at the two ends of the proposed tunnel could be readily ascertained, and thus a reliable estimate of the cost of the work could be formed. But if the strata were not horizontal, then even the most careful examination of the rocks at either end of the proposed tunnel might deceive the engineer who had neglected to ascertain the geological structure. The accompanying diagram (Fig. 135) represents the geological structure of a hill which it is proposed to tunnel along the line *a—b*. It is obvious that shallow pits and borings put down over the surface can give no indication of the nature of the rocks which the tunnel is likely to pierce. An engineer, finding that the rock over the top of the hill and at the two extremities of the proposed tunnel were all of a reliable kind, might probably conclude that the whole hill was composed of like materials. If the rock happened to be of a self-supporting nature—one that required little or no expensive building—he would frame his estimates of cost accordingly. A knowledge of the actual structure, however, would have shown him that the self-supporting stratum could continue but a short distance on the level of the proposed tunnel, and would then be succeeded by friable shales requiring support all the way to near the middle of the hill, where highly porous and water-logged sandstones might be expected to add still further to the difficulties and cost of the undertaking. The history of engineering operations in this and other countries is full of warnings as to the danger of driving tunnels without having first determined the geological structure of the ground. Not infrequently, this requisite knowledge might have enabled the engineer to avoid difficulties and greatly increased cost by some slight deviation of the line of his tunnel or by modifying the gradients. Even in cases where such deviations and modifications may be impossible, a knowledge of the difficulties lying before him would yet greatly aid the engineer in making his estimates.

Foundations.—Engineers and architects are necessarily called upon to consider the nature of the foundations on which it is proposed to build heavy structures. Trial holes will show the nature of the materials, but they do not always disclose the geological structure, and in the case of very heavy buildings it is absolutely essential that the latter should be carefully ascertained. For, however solid and unyielding the substratum may seem to be, calculations as to its stability are liable to error if its relations to the immediately subjacent rocks be not taken into account. For example, a firm massive sandstone may be underlaid by some impervious slippery clay, which, should the strata have a decided dip, may yield to the great pressure of a heavy superstructure, and cause the rock-foundation to slide forward along the plane of bedding. Unconsolidated materials often make bad foundations, but tough, homogeneous clay, if of sufficient thickness, is usually reliable. Alluvial or superficial deposits of every kind, however, are as a rule unsatisfactory, and, in the case of important structures, usually require special treatment, involving often costly excavation, the driving of strong and closely set piles, and the formation of an artificial foundation of concrete. Although tough clays, such as the boulder-clay of the Scottish Lowlands, usually form reliable foundations, they nevertheless are sometimes untrustworthy. Not infrequently they contain layers and beds of gravel and sand that carry water, which, when it escapes at the surface, tends to undermine the overlying mass, and thus in time causes the ground to subside. Before any heavy building is raised upon till, therefore, it is necessary to ascertain by means of boring whether any water-bearing beds be present. The river-valleys of Central Scotland afford many examples of the relative instability of boulder-clay, when that deposit rests upon an inclined surface of rock. In the valley of the Esk, Midlothian, for example, houses and walls built upon the slopes overlooking the stream almost always afford evidence in their cracked masonry of a slow and interrupted but nevertheless continuous slipping of the foundations. The cause is obvious : the boulder-clay, which has a coarse, rubbly bottom, rests upon an inclined surface of sandstones, shales, etc., from which water escapes and percolates through the stony and rubbly base of the clay. The latter thus becomes softened and slippery, and from time to time yields, and the mass creeps downwards. The boulder-clay, under such conditions, is in a state of unstable equilibrium, the risk of slipping increasing with the slope of the surface on which the clay reclines.

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CHAPTER XXIII

ECONOMIC ASPECTS OF GEOLOGICAL STRUCTURE—*continued*

Water-supply. Lakes and Impounded Streams. Reservoirs. Supply from Rivers. Underground Water—the Water-table; Natural Springs as illustrating the course followed by Subterranean Water; Surface and Deep-seated Springs. Common Wells and Driven Wells. Artesian Wells. Considerations to be kept in view in the Search for an Artesian Water-supply. Drainage.

Water-supply. — Superficial and underground sources of supply alike depend upon the amount of precipitation and the physical aspect and geological conditions of a country. But the relative amount of water circulating above and below ground respectively is determined mainly by the character of the rocks and the mode of their arrangement. Two regions, for example, may have the same amount of rainfall, and, nevertheless, the one may be little better than a dry desert, while the other may rejoice in numerous streams and rivers, and be conspicuous for its fertility. There are many lands that consist of rocks so highly pervious that rain and melting snow at once descend below the surface, and streams and rivers are impossible, all the drainage being conducted underground. On the other hand, we may encounter elsewhere the opposite extreme, namely, a country built up of impermeable rocks which absorb so little water that practically the entire rainfall flows in superficial courses to the sea. Between these two extremes there are many gradations, most lands being composed partly of porous and partly of impermeable rock-formations.

It will be convenient to treat of the water-supply derived from superficial sources apart from that obtained from underground stores, although it is obvious that much of the water that circulates in our streams and rivers has come from springs.

Lakes and **Impounded Streams.**—The character of the water of a lake naturally depends upon that of the catchment area, for it is needless to say that the level of the lake is maintained by the rainfall—in other words, by the springs and streams that feed it. Should the rocks within the drainage area be largely calcareous the water will be *hard*; should igneous and schistose rocks predominate, the water will be moderately *soft*. Other things being equal, the deeper and larger a lake is, the purer and colder must the water be. Large and deep lakes occupying mountain valleys, like those of our own islands, where there is little or no cultivation and not much chance, therefore, of contamination, are always desirable sources of water-supply. But every country is not so fortunate in the possession of large natural reservoirs, and even when these exist they are often so far removed from centres of population as to be practically beyond reach. Under such circumstances, engineers are required to form artificial lakes by impounding streams.

Reservoirs.—The formation of reservoirs is purely an engineering operation, but, like many other undertakings of the kind, it ought to be conducted with a full knowledge of the geological conditions. If we have the choice of several streams, it is obvious we should select the purest. Those which are most likely to yield a desirable water-supply will usually occur in sparsely cultivated districts which are not likely in the future to attract much population, such as the high-lying pastoral regions of our own country. Before selecting a stream, however, the character of the rocks within the drainage-area should be carefully inspected, for the purpose of ascertaining whether these contain deleterious ingredients which might unduly affect the character of the water-supply. Usually, however, careful chemical analyses of the water flowing in the main stream at all seasons of the year will determine the suitability or otherwise of the supply. A desirable stream having been obtained, the engineer's next care is to select a site or sites for his storage reservoirs. It is at this stage of his work that he will find a knowledge of structural geology most helpful. He should carefully investigate the rocks occupying the proposed site, in order to satisfy himself as to their soundness. Should they be very porous and much shattered and jointed, the conditions will be unfavourable, and a better site, if possible, should be sought for. This will be all the more advisable should the strata in question be inclined in the same direction as the valley, for under such conditions leakage is almost certain to take place—much water escaping along the bedding-planes, not to reappear at the surface, perhaps, till after an underground course of many miles. Should the inclination of the strata, however, be in the opposite direction, there is not the same danger of considerable loss, since any water that finds its way below the surface may possibly be discharged again farther up the valley. It is needless to say, however, that no engineer would think of forming a reservoir over an area of highly jointed and pervious rocks, if he could avoid doing so. Unfortunately, the bottom of a valley is frequently covered with thick alluvial deposits, and the engineer, unless he knows something of geological structure, may not be aware of the nature and arrangement of the underlying rocks, even after he has tested the ground by means of bore-holes.

The selection of a site for his *embankment* demands the greatest care. Sometimes there is no difficulty—the bed of the valley may be deeply filled with tough, homogeneous clay, than which no better foundation could be obtained. It is always well, however, to make sure by a series of borings that no water-bearing beds are present in or underneath the clay; for in either case these would be sources of danger, allowing of leakage, and thus threatening the stability of the embankment. As foundations for an embankment, highly jointed rocks of any kind—certain igneous rocks, limestones, and loose shattery shales especially—are to be avoided. When the engineer has no choice of sites, but must, if at all possible, build his embankment upon rocks, the character and structure of which are quite unfavourable, the difficulties he must encounter will add greatly to the cost of the undertaking.

Rivers.—Some towns and cities draw their water-supplies from the rivers on which they are situated. In certain cases the water is pumped from some point above a town, while in other cases it is drawn from the higher reaches of the river and brought in open courses or in pipes. This source of supply is seldom desirable; but not infrequently no other source is available, in which case the only thing to be done is to look well after the filtering, which doubtless minimises the danger of pollution, but cannot always be implicitly relied upon to protect the population. It is remarkable, however, how rapidly rivers seem to purify themselves from the pollutions poured into them by the villages and towns upon their banks. Soon the water begins to clear, a foul-smelling mud settling upon the stones and gravel of their beds, and gathering here and there in extra quantities along their margins. Exposed to sunlight and the action of the atmosphere, the various organic impurities become broken up—a process in which numerous minute forms of life play a not unimportant part—until eventually the river may become bright and sparkling as at first. All such waters, however, are properly held suspect, and ought never to be used for domestic purposes before they have been carefully examined and declared safe.

Underground Water.—The proportion of the rainfall that sinks into the ground naturally varies according to the character of the underlying rocks. But, whatsoever the nature of the rocks may be, they are commonly charged with water up to a certain limit known as the **water-level** or **water-table,** the depth of which from the surface is determined by the amount of rainfall, the configuration of the surface, and the geological conditions. In some districts the level in question may be reached at only a few yards down; in other places it may sink to great depths, and it usually fluctuates with the rainfall. Owing to these several conditions a constant underground circulation is kept up, gravitation and hydrostatic pressure forcing the water through the pores and fissures of the rocks until it can escape at the surface in the form of springs. In regions composed chiefly of highly pervious rocks of great thickness springs are of infrequent occurrence, and are apt to appear only in the deeper depressions of the land. But in countries where the rocks are of variable character and structure, underground water may be discharged at many different levels, in mountain regions and low grounds alike; not infrequently, indeed, copious springs of fresh water coming from such regions issue on the floor of the sea. The various divisional planes of rocks—joints, bedding-planes, faults, etc.—naturally constitute the chief underground water-ways. In the case of soluble rocks these water-ways become widened by the chemical and mechanical action of the running water, until very considerable tunnels may be worked out, giving passage to torrents, streams, and rivers. Relatively insoluble rocks are not, of course, traversed by subterranean channels of this kind, but, if sufficiently porous, they frequently contain enormous stores of water. When such beds are inclined and underlaid by impermeable strata, the water they contain naturally makes its way downward in the direction of dip. Should the strata be horizontal, underground flowage nevertheless does not cease, the water under hydrostatic pressure being forced to percolate through the rocks. Such movements, indeed, necessarily take place even in amorphous rocks which are neither bedded nor jointed.

In the following case (Fig. 136) we have, say, an amorphous mass of sand and gravel (*a*) resting upon a horizontal surface of impervious clay (*b*). Rain falling on the surface of *a* is greedily absorbed, and gradually sinks until the bed becomes saturated up to a certain limit (*w*), when the frictional resistance to its passage outwards is overcome by the hydrostatic pressure. It is then forced to flow along the surface of the underlying clay, and escapes to the light of day at *s s* as a line of seepage, marking the junction between the porous and impervious beds; but should there be irregularities in the surface of the clay it may issue in the form of definite springs. Springs of this kind are of common occurrence in horizontally bedded rocks of varying character, some being pervious, others impervious; for every porous stratum is likely to contain a store of water which will ooze or flow out wherever the beds are truncated, as on hill-slopes and in valleys (Fig. 137).

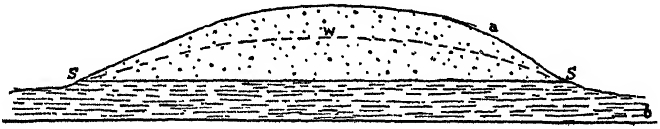

FIG. 136.—HEAPING-UP OF WATER IN SUPERFICIAL DEPOSITS.

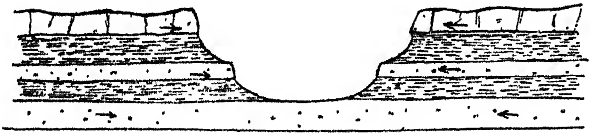

FIG. 137.—DRAINAGE IN HORIZONTAL STRATA.
The arrows indicate direction of drain age.

Generally, however, strata are more frequently inclined than horizontal, and through these water flows under the combined influence of gravitation and hydrostatic pressure. When such strata are traversed by a valley running in the direction of strike, underground water tends to be discharged only on one side, namely, on that side from which the truncated beds dip into the valley. If the beds dip at a high angle, the springs will usually be insignificant, since with a high dip the outcrops will be narrow; with a low dip, on the other hand, the discharge will be proportionately greater, for the simple reason that the outcrops of the porous beds will spread over a wider area, and be thus capable of imbibing a large proportion of the rainfall.

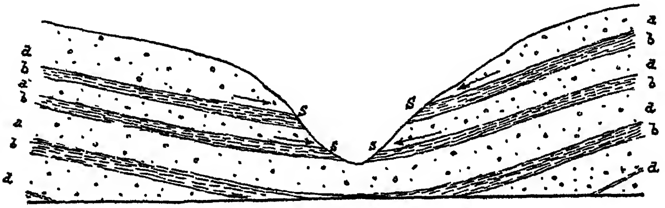

Fig. 138.—Drainage in Synclinal Strata.

a, *a* = pervious beds; *b*, *b* = impervious beds; *s*, *s* = springs.

Synclinal valleys are of rare occurrence, especially in regions which have experienced much denudation; but when they do occur amongst water-bearing and impervious strata, springs may abound on both sides of a valley (Fig. 138). When a valley coincides with an anticline, however, the geological structure is obviously quite unfavourable to the outflow of underground water, the water, as in the previous cases, making its way in the direction of dip (Fig. 139), and therefore away from the valley.

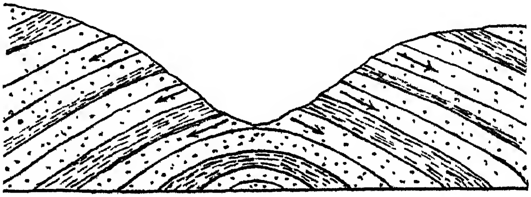

Fig. 139.—Drainage in Anticlinal Strata.

Arrows indicate direction of drainage.

We have been considering the flow of water through porous rocks as being conducted along the planes of bedding; but we must not forget that sedimentary strata are traversed by joint-planes, and that the presence of these naturally influences the circulation. When all the porous beds in a series of strata are fully saturated, the water will follow the normal direction. But when continued dry conditions have cut off the supply from above, and the discharge by springs begins to diminish, water seeks its way down through joints and fissures from one porous bed to another. Hence the springs issuing from the deepest beds will continue to yield their usual supply long after the highest lying springs have failed. The exhaustion of the springs may be still further delayed by the exuding of water from the less porous beds—all of which, although spoken of as impermeable, are yet capable of absorbing and giving out water in less or greater degree.

Springs are not less characteristic of massive eruptive rocks than of sedimentary beds; but while the underground drainage of the latter is conducted principally through porous strata, and therefore follows a determinate direction, that of the former keeps to the clefts and fissures, and as these vary in width and trend, and may be numerous in some places and far apart elsewhere, one never can tell where springs are likely to appear at the surface. Rain falling upon a granite mass finds its way down through innumerable fissures, and after a relatively short downward course may, under the influence of gravity alone, escape to the surface. Or after penetrating to a great depth—far below the level, perhaps, of any valley in the neighbourhood—it may have its passage impeded or barred by the closeness of the joints. Subject to great hydrostatic pressure, it will now be forced to ascend to the surface along the same kinds of fissures by which it travelled downwards, and will issue as a deep-seated spring, which may or may not have a temperature exceeding that of the region where it appears. It is not improbable, indeed, that meteoric water may sometimes descend by fissures to such depths that its further progress downward is arrested by the internal heat of the earth. The enormous pressure at a depth of several thousand feet will prevent ebullition; but expansion must result, and this, added to the hydrostatic pressure of the descending currents, will force the water through other fissures to the surface. Deep-seated springs of such a nature might either be cold or thermal (Fig. 140).

The underground drainage of schistose rocks is usually just as hard to determine as that of massive eruptives.

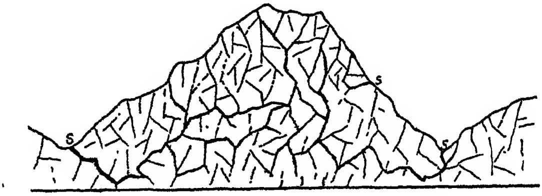

Fig. 140.—Drainage in Massive Igneous Rock.

s, *s* = springs.

Exceptionally, where schists are relatively well bedded and consist of a series of rocks, some of which are better water-bearers than others, springs will tend to appear at the outcrops of the latter. As a rule, however, owing to the abundant folding and the irregular jointing, the direction of the underground drainage among schistose rocks is quite indeterminate.

A large number of strong springs often appear along the line of junction between an intrusive mass and the rocks it traverses. The water may be derived either from the one or the other, or from both. In Fig. 141, for example, a great mass of granitoid rock is represented cutting across a series of relatively impervious strata. The rain passes downwards through the much-jointed eruptive mass, where it accumulates. The water cannot escape laterally, because it is dammed back by the impervious beds (*b*); it therefore continues to accumu-

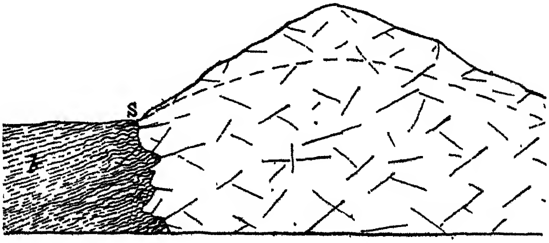

Fig. 141.—Heaping-up of Water in Igneous Rock.

late until it reaches the point where the line of junction comes to the surface. Here, under hydrostatic pressure, it flows out as a more or less copious spring (*s*) or line of springs. In many cases, however, the water is derived from the stratified rocks rather than the intrusive mass by which they are intersected. In Fig. 142 the strata, consisting of pervious and impervious rocks, dip towards the igneous mass. Water soaking through the porous beds (*p*) is dammed back by the basalt (*b*) and forced to the surface (*s*) along the junction-line. Now and again, the water discharged under such conditions would seem to come from the rocks on both sides of the junction, especially when the igneous mass is of the nature of a batholith, and exposed at the surface over a considerable area.

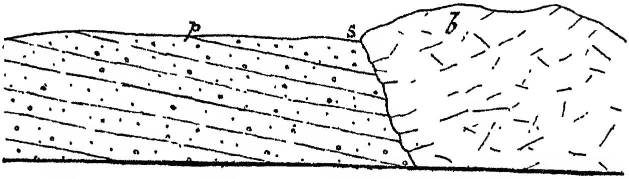

Fig. 142.—Interception of Underground Drainage by Intrusive Rock.

Springs, as we have already seen, are often associated with those vertical wall-like intrusions known as dykes (see p. 199). When dykes cut across inclined rocks in the general direction of the strike they naturally act as subterranean dams, interrupting the underground water flowing towards them, and forcing it to rise to the surface (Fig. 143). Junction-springs of this kind are very common in Scotland. Probably the most important springs of all, however, are those that appear on lines of faulting or dislocation. These, as we have learned, frequently bring permeable against impermeable

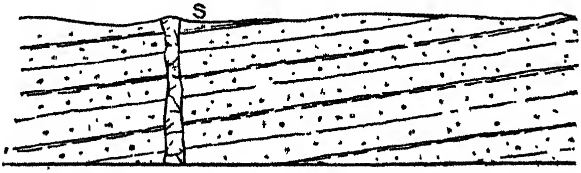

Fig. 143.—Interception of Underground Drainage by Dyke.

rocks, and many of the largest dislocations run in the direction of the strike of inclined strata. Hence, when a series of porous strata dip at a low angle for a long distance towards one of these faults, on the other side of which the rocks are more or less impermeable, all the conditions favour the formation of strong springs (Fig. 144). Even when the strata on both sides of a fault are porous, springs will usually indicate its presence, for faults are often filled or lined with clay, etc., and thus form more or less impervious barriers; while the adjacent rocks, commonly much fissured and fractured, afford the underground water a ready passage to the surface. A fault traversing horizontal strata in such a way as to bring permeable and impermeable rocks into juxtaposition likewise causes springs to appear, whenever the water-level in the porous beds reaches the point where the fault touches the surface (Fig. 145), the conditions being somewhat comparable to those represented in Fig. 141. Considerable dislocations, indeed, will usually carry water, even although the structure of the rocks they traverse may not seem very promising. For it will rarely happen that a normal fault, cutting across a great thickness of rock, will not, in some parts of its course, truncate water-bearing beds, the fluid

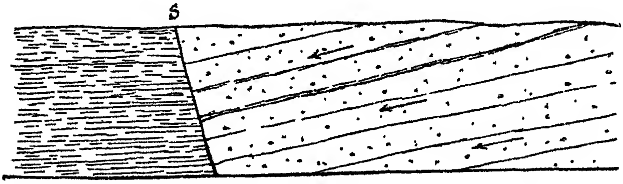

FIG. 144.—INTERCEPTION OF UNDERGROUND DRAINAGE BY FAULT.

Arrows indicate direction of drainage; *s* = spring.

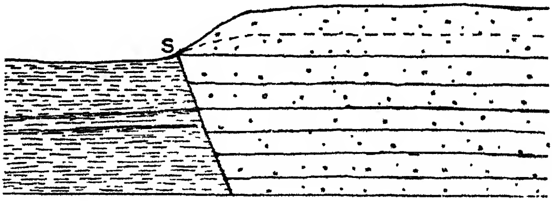

FIG. 145.—HEAPING-UP OF WATER IN HORIZONTAL STRATA.

contents of which are under sufficient hydrostatic pressure to rise to the surface. The faults themselves are often to some extent open fissures or filled with rock-rubbish which is easily penetrated, while the contiguous rocks on one or both sides are usually more or less fractured and jumbled; it is not surprising, therefore, that springs should occur along lines of dislocation under the most diverse conditions. It will thus be seen that a knowledge of the faults of a district is highly desirable, if we would understand its subterranean hydrography.

Springs are usually classified as *shallow* or *surface* and *deep-seated.* A spring which fluctuates with the seasons—tepid in summer and cold in winter, and running full or drying up according as the rainfall is excessive or scanty—is obviously quite superficial, the water having come no great distance. Between temporary springs of this type and perennial springs whose volume remains practically constant, and whose temperature does not vary with the seasons, there are all gradations. Obviously, the most persistent springs derive their supplies from wide gathering grounds, those whose surface never rises nor falls probably coming from the greater depths.

Wells.—The foregoing rapid sketch of the conditions that determine the underground circulation of water and its discharge at the surface will suffice to indicate what course we should follow in searching for a subterranean water-supply. From the very earliest times, men have dug for water—a **common well** being simply a hole sunk below the water-level, into which percolation from the surrounding rocks takes place. In these advanced days, we now imitate Nature on a bolder scale, and by means of our bore-holes produce more or less deep-seated perennial springs. Water is doubtless very generally distributed through the superficial parts of the earth's crust; but all rocks, as we have learned, are not equally absorbent, and the depth of the water-level from the surface is very variable. It is obvious, therefore, that before proceeding to sink a common well, we should first ascertain whether the geological conditions are favourable or not. If the rocks of the district be highly jointed and pervious we are unlikely to succeed; but if they be less fissured, there is some hope of reaching the water-level at a moderate depth. It is needless, however, to say that much will depend upon the climatic conditions of the region, for the position of the water-level is necessarily largely determined by the rainfall.

The superficial accumulations of this and many other countries not infrequently contain large quantities of water, either derived directly from the rainfall or introduced into them by natural springs, while in other cases it has filtered into them from streams. Sheets of sand, for example, which are underlaid and perhaps overlaid by impervious clay, usually hold water. Again, the recent alluvia of our rivers, and the more ancient flats and terraces of similar materials which occur so frequently at various levels in our valleys, may yield copious supplies. The water obtained from the younger alluvia has obviously percolated into them from the adjacent stream or river. The older alluvia, on the other hand, have usually derived theirs from the valley-slopes—a very superficial supply—but now and again the water flows into them from true springs issuing into or underneath the deposits. Common wells, dug in superficial deposits of the kind referred to, not infrequently yield a good supply of potable water, but they are not always to be trusted. Near towns and villages, and even in the vicinity of isolated dwellings, they are liable to contamination, impurities being readily filtered into them, especially during wet seasons. The wells sunk in an old river-terrace may, under ordinary conditions, yield excellent water, more particularly when the parent source of the supply is a spring discharging into the deposits. In times of heavy flood, however, when the adjacent river rises to the level of the terrace, the gravel is rapidly saturated, and impurities may be washed into the wells. The fact that when the rivers are in flood, outbreaks of typhoid fever often occur in riparian districts supplied from such wells is sufficiently suggestive. The water, which under ordinary conditions is quite wholesome and suitable for all domestic purposes, is, perhaps, never suspected, and may continue to be used until the next considerable flood repeats the work of its predecessor.

In certain districts deeply covered with loose deposits of gravel, sand, clay, etc., it is often difficult or practically impossible to sink common wells for a local water-supply. When such is the case, engineers often have recourse to **driven wells.** These are made by forcing down a strongly pointed iron pipe, pierced with holes round the bottom to admit the water. The advantages of this system are obvious, for not only can the pipe be driven to depths much below those reached by any ordinary well, but the water-supply obtained is protected from impurities coming from the surface. In populous districts, however, even driven wells may in time become polluted, for the pipe, subject to the corrosive action of foul liquids descending from the surface, may eventually yield admission to the enemy.

When good springs are not available, common wells are often the only source of supply in country districts. In sinking these it is always advisable to take the geological conditions into consideration. Remembering that underground water finds its way in the direction of dip, care should be taken to sink wells in such positions that impure surface water cannot reach them by percolating along the bedding-planes. It is absolutely necessary, moreover, that wells should be placed as far away as possible from dwelling-houses, cesspools, drains, etc., and every possible source of pollution. Frequently, indeed, it may be found necessary to line them with water-tight walls, especially in the case of wells that are sunk in more or less unconsolidated deposits. Even after every precaution is taken, however, no surface-well can be considered perfectly safe, although there are some obviously more liable to be contaminated than others. Wells sunk in river alluvia, in proximity to and upon the same level as dwelling-houses, are the most dangerous of all.

Artesian Wells.—The driven wells referred to above are often true artesian wells on a small scale, for an artesian well is simply a bore-hole sunk to some permeable stratum in which the water is under such high pressure that when it is reached it rises towards the surface, the upper limit reached by it being determined by the height of its head or source above the mouth of the well, and the amount of frictional resistance it has to overcome. Should the latter be very great, there may be no rapid rise of water in the well. The rock may be porous enough in texture, but if it be not traversed by more or less open joints and fissures, the hydrostatic pressure may barely suffice to keep up a gentle circulation. Fortunately, such planes of division are seldom or never absent, and in certain rocks, as we have learned, they are often relatively wide and open.

The accompanying diagram (Fig. 146) will serve to indicate the geological conditions under which an artesian water-supply is obtained. The section is supposed to be taken across a broad area, throughout which the strata, consisting of pervious (*p*) and impervious (*imp*) beds, are arranged in a basin-shaped form. Rain falling on the outcrops of the pervious beds, which are overlaid and underlaid by impermeable strata, percolates in the direction of the bedding-planes, and accumulates until each porous stratum becomes saturated up to its outcrop. It is obvious that this imprisoned water must be under hydrostatic pressure, which necessarily increases with the depth and reaches a maximum in the centre of the basin. Were a boring made at 1 through the uppermost impervious stratum into the subjacent water-logged bed, an uprush of water to the surface would ensue. At first, the water might form a tall fountain, the height of which would be determined not only by hydrostatic pressure, but by the amount of frictional resistance to be overcome by the water. If the passage of the water through the porous bed were favoured by open fissures, the fountain might reach a height not very much below that of the outcrop of the bed. Shortly, however, it would begin to decrease in height until it reached a level determined by the average rainfall of the district. It would, in fact, behave like a perennial spring. A boring sunk at 2 would tap a deeper stratum, and cause a still stronger outflow owing to the greater head; while the beds tapped by 3 and 4 would for a similar reason send yet more powerful uprushes of water to the surface.

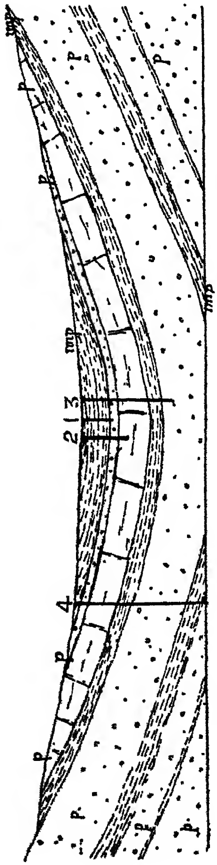

FIG. 146.—ARTESIAN WELLS.

The geological conditions represented in the diagram are, of course, ideal. Each pervious stratum is supposed to retain all the rain-water which soaks into it at its outcrop. In point of fact, however, such conditions rarely if ever do obtain. So-called impervious strata are only relatively non-porous, while continuous joints and other lines of fissure, traversing all the beds of a series alike, are so seldom absent that the water in deeply buried pervious beds must in less or greater degree escape towards the surface. Hence, when an artesian well is sunk, the water does not always rise so high as might have been anticipated, even after allowance has been made for frictional resistance. It must not be supposed that a basin-shaped arrangement of the strata is essential for the formation of artesian wells. Any series of impermeable and permeable beds, dipping continuously in one direction for some considerable distance, may contain abundant supplies which, under certain conditions, can be reached by boring. Some of these conditions may therefore be briefly considered.

A well-jointed porous bed, or series of beds, underlaid and overlaid by impermeable strata, may thin-out gradually in the direction of dip, and when such is the case they become water-logged (Fig. 147). Or the descent of water along the bedding-planes may be interrupted, not by the thinning-out of beds but by such barriers as have already been referred to—faults, dykes, and other discordant junctions. Or, in the absence of any underground dams, the descending water may be stopped at extreme depths by the increasing temperature, the hydrostatic pressure being eventually counterbalanced by the tension of superheated steam. It is under such conditions as these that many natural springs originate; the imprisoned water seeking to escape pressure tends to rise through joints or other lines of weakness towards the surface. Sometimes, however, it is prevented doing so, or is only partially successful, and immense stores are thus often retained underground. Such hidden sources are not difficult to discover, especially in regions the geological

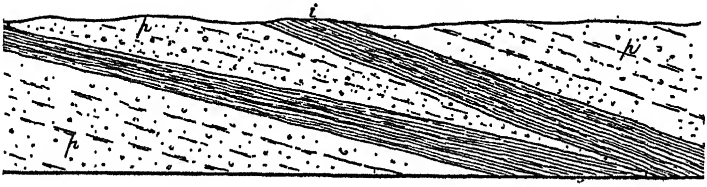

FIG. 147.—WATER-BEARING BEDS WEDGING OUT DOWNWARDS.

p, *p* = pervious beds; *i* = impervious beds.

structure of which can be readily ascertained from a study of the rocks exposed at the surface.

The more important points to be considered in the search for an artesian water-supply may be summarised as follows :—

1. Having ascertained that the strata over a wide region have a dominant dip in one direction, we must endeavour to acquire as complete a knowledge as possible of the various rocks and rock-groups. It is essential for success that pervious beds should occur interstratified with impermeable strata, the best kinds of water-bearing beds being sand and gravel, sandstone, grit, conglomerate, and highly fissured limestones.

2. The thickness of the entire succession of strata should be carefully measured, and the precise position in the series of any water-bearing beds should be ascertained.

3. It is, further, most important that the average angle of dip should be determined, otherwise we shall be unable to estimate the depth from the surface at which the water-bearing beds may be expected to occur at any given point.

4. The inclination of the strata must not be too great, for obvious reasons: (*a*) Gently inclined strata have relatively broad outcrops, and therefore are in a position to absorb more rain than if they had been highly inclined or vertical. Thus, the outcrops of a series of strata, 100 feet thick, dipping at angle of 1°, would be rather more than a mile in width; while, if the angle of dip were 5°, the width of outcrop would be only 350 yards or thereabout—the width necessarily varying inversely as the dip; (*b*) With an inclination of only 1°, a stratum descends about 30 yards in a mile; but a dip of 5° carries it down 147 yards in the same distance; while at angles of 10°, 20°, and 40°, the depths at which the stratum would occur would be about 300, 630, and 1490 yards respectively. It is obvious, therefore, that with a high dip a water-bearing bed must within a short distance descend to a greater depth than the engineer might consider it possible or desirable to bore.

5. Let us suppose, however, that we have assured ourselves that the character of the strata is quite satisfactory, and that their inclination is equally favourable; we have still to ascertain whether the region is traversed by faults, dykes, or other discordant junctions which may serve as sub-

terranean dams. It is quite obvious that, if any such obstructions occur, their position must influence the engineer in selecting a site for an artesian well. It would be hopeless to bore for water on the dip-side of a strike-fault or a dyke following approximately the same direction, whereas a boring put down on the rise-side would in most cases be successful.

6. When the strata consist throughout of pervious beds—such as sandstones, highly cleft limestones, etc.—the chances of obtaining an artesian water-supply are much diminished. Nevertheless, even in such cases, there will in all probability be some closer grained or relatively impervious bed or beds to stay the downward passage of the water. An extended survey of adjoining districts may even show that the pervious beds, as they range beyond our region, are underlaid by or interosculate with impervious beds; or that, in the direction of the dip, they are eventually interrupted by faults, dykes, or other barriers, and may not, therefore, be so barren of water at a moderate depth as appearances in our own neighbourhood might have led us to infer. Should the whole area be more or less deeply mantled with impervious superficial accumulations, such as boulder-clay, the prospects of obtaining water by boring would be considerably increased.

7. It goes without saying that the water obtained from a bore-hole, although sufficiently abundant, may yet be unsuitable for the purpose the engineer has in view. A careful survey of the catchment area should, therefore, be made preliminary to any boring. It may be that some of the pervious beds contain deleterious ingredients, which must unfavourably affect the quality of the water; while, at other horizons, water-bearing strata of a satisfactory character occur. Should it be necessary to pass through an undesirable source of supply to reach a more promising source at a lower level, the water coming from the higher level can be prevented from contaminating that of the lower level by simply tubing it off. Another danger is the infiltration of foul liquids from the surface. These may not penetrate sufficiently far to affect the water at the relatively deep level from which it is drawn. But unless the bore-hole is properly tubed for some distance down from the surface, it is likely enough to be invaded by pollutions.

Drainage.—In planning a scheme of drainage either for town or country, it is not enough to consider only the natural slope of the ground, and the ease with which the waste products of a community can be discharged elsewhere. It must be remembered that the external configuration of the ground may not coincide even approximately with the internal or geological structure. The surface may slope in one direction and the subjacent strata in quite another. There is always a danger, therefore, of polluted liquid finding its way down the bedding-planes, and poisoning the underground water-supply of adjacent districts. It is, of course, often necessary to carry drains in some given direction other than that which geological considerations might dictate, for questions of safe outlet and the expense of excavation cannot be ignored. In cases of this kind, all the engineer can do is to see that the drains are made as water-tight as may be, and to insist on the closing of every common well in the immediate neighbourhood. Flat lands in the neighbourhood of considerable towns are sometimes laid out as sewage-fields, with satisfactory results, it may be, to the towns, but often much to the prejudice of a scattered rural population, whose water-supply may come entirely from common wells. Whatever excuse there may be for carrying the drainage of a city in some particular direction, irrespective of geological considerations, there can be none for discharging sewage over the surface of the ground without preliminary inquiry as to what may happen in the event of leakage into the rocks below. Cases could be cited to show how neglect of this precaution has been followed by disastrous results. Some low-lying fields were selected by a certain town for sewage irrigation. The subsoil was boulder-clay, a deposit supposed by the engineers to be impervious. But there are boulder-clays and boulder-clays; many are practically impermeable, others are only relatively so. This particular boulder-clay was one of the latter class, somewhat sandy in texture, and only two or three feet at most in thickness. Unfortunately, also, the sewage-field spread over the back of a low anticlinal arch. Under those conditions the inevitable result followed in due time. In a year or so the subsoil of boulder-clay became water-logged, leakage took place into the underlying strata, and the foul liquid made its way down the bedding-planes and poisoned all the springs and common wells in the surrounding neighbourhood, typhoid fever, of course, ensuing.

In villages and rural districts, where no general system of sewerage is provided, cesspools are often sunk. When these are carried down through a thick bed of clay into underlying gravel and sand, they may suit the purpose of their owners well enough. It is obvious, however, that they are a menace to the neighbourhood, and that, in time, springs and common wells may become polluted. This primitive kind of drainage is only permissible in new countries where the population is sparsely scattered. It should not be tolerated in a populous region, that is dependent for its water-supply on wells and springs, without the most careful inquiry into the geological conditions.

Low-lying lands with a very gentle slope are often cold and wet, or even swampy and boggy. Surface drains in such cases may be quite useless, owing to the low gradients. Very often it is the presence of an impermeable hard pan at the depth of a foot or two below the surface, which prevents the escape of the water. With the breaking-up of this " pan " the superficial water filters into underlying porous beds, and the land is at once improved. Occasionally, the barrier to the escape of superficial drainage is more deeply seated, and may be due to the occurrence of some thick impervious stratum of clay, shale, etc., either occupying the surface or appearing immediately underneath overlying porous beds. In such a case, if no outlet can be obtained by surface-draining, it is sometimes possible to sink pits or to bore through the impermeable stratum into underlying beds which are porous, and through which the superficial water eventually drains away.

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CHAPTER XXIV

SOILS AND SUBSOILS

Rock-disintegration; Insolation and Deflation; Rain; Frost; Life. Weathering of Rocks. The Soil-cap. Classification of Soils—I. Bed-rock Soils, their Varied Character; Soils derived from Igneous, Metamorphic, and Derivative Rocks. II. Drift Soils; Glacial. Alluvial, and Æolian Soils. Climate and Soil Formation. Soil Deterioration and Soil Erosion.

Rock-disintegration.—Subsoil has already been defined as an unconsolidated heterogeneous aggregate of disintegrated rock material, and soil as essentially the same, with the addition of organic matter. Both are the result of the operation of various epigene agents, and are therefore properly included among *derivative rocks*. Everywhere throughout the world we meet with these superficial accumulations. As might have been expected, they vary in character according to the conditions under which they have been formed, and the nature of the rocks from which they have been derived. In some regions, for example, they consist largely of angular and subangular detritus, while in other places they may consist mainly of sand or of clay, as the case may be. In high latitudes and in mountainous lands the soil-cap is usually very stony; in lower latitudes and over plains and gently undulating tracts its ingredients are commonly finer grained. In most regions, however, arable soils are composed essentially of insoluble quartz-sand and clay, in ever-varying proportions, throughout which are disseminated larger or smaller percentages of organic matter and of certain more or less soluble ingredients, such as compounds of iron, magnesium, calcium, sodium, potassium, etc.

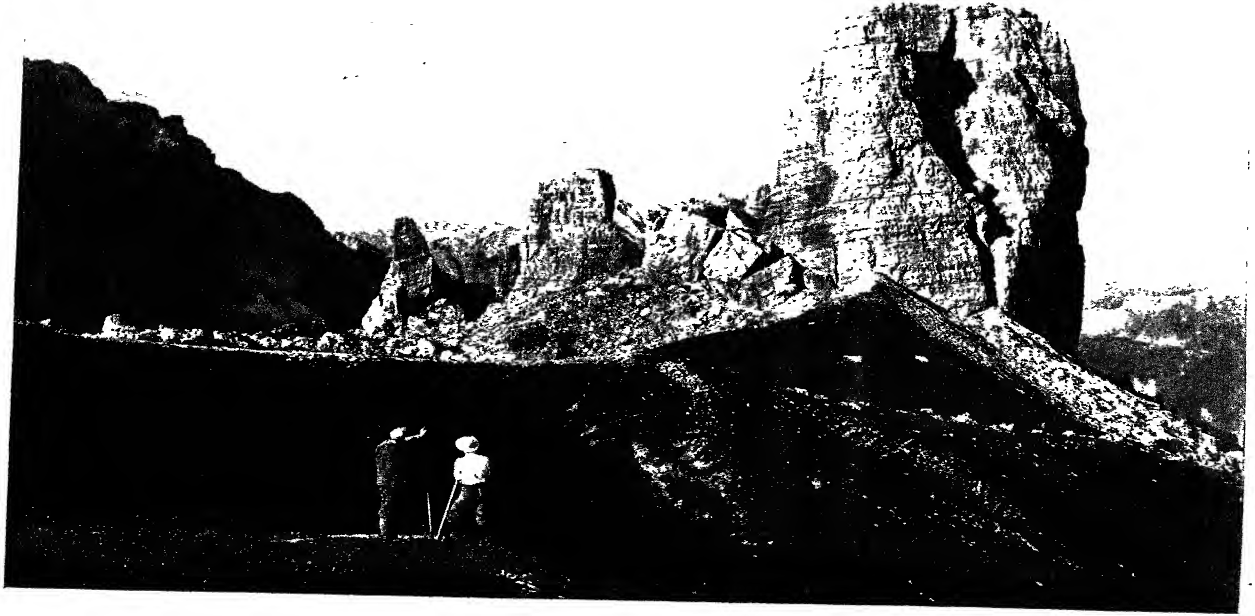
In preceding pages, frequent reference has been made to the alterations and transformations of minerals and rocks induced by epigene action. Again, while dealing with the structural phenomena of derivative rocks, we have briefly considered the various origins of sedimentary deposits. The remarks that follow, therefore, may be taken as a kind of summary of much that has already been advanced on the subject of rock-disintegration, illustrated by special reference to the geological origin of soils and subsoils.

Insolation and **Deflation.**—Among the various agencies that tend to disintegrate rocks, and to form a soil-cap, are changes of temperature. Rock-surfaces are heated by day and in summer time—cooled at night and during winter. They thus alternately expand and contract, and this leads to disintegration, for their constituent minerals often yield unequally to strain or tension. Such is notably the case with rocks composed of minerals differing in colour, density, and expansibility, such as granite, gneiss, diorite, etc. Even in the case of homogeneous rocks, it is obvious that alternate heating and cooling of the surface must give rise to strain and tension. In countries like our own, where there is no great diurnal range of temperature, any rock-changes due to this cause alone are hardly noticeable, since they are masked or obscured by the action of other and more potent agents. But in the rocky deserts of tropical and subtropical regions, bare of verdure and practically rainless, the effects produced by alternate heating and cooling, or "insolation" as the process is termed, are very marked. The rocks are cracked and shattered to a depth of several inches; the surfaces peel off and are rapidly disintegrated and pulverised. Wind then catches up the loose material and sweeps it away, leaving fresh surfaces exposed to the same destructive action. More than this, the grit, sand, and dust carried off by the wind are used as a sand-blast to abrade and erode the rocks against which they strike. In this manner cliffs and projecting rocks are undermined, and masses from time to time give way and fall to the ground, where, subject to the same grinding action, especially towards the base, they tend to assume the appearance of irregular blocks supported upon pedestals. "Deflation," or the transporting action of the wind, goes on without ceasing, with the general result that the whole surface of a rainless region tends to be gradually lowered, the loose materials travelling outwards from the scene of their origin to the borders of the desert.

Action of Rain.—Even in countries like our own, insolation and deflation doubtless share in the disintegration of rocks and the transport of the loosened materials. Undoubtedly, however, in these latitudes, the most conspicuous agents employed in the work of reducing rocks to the condition of grit, sand, and clay, are rain and frost. Rain always contains some oxygen and carbonic acid absorbed from the atmosphere, and after it reaches the ground still larger stores are derived by it from the decaying vegetable and animal matter with which soils are more or less impregnated. It is thus enabled to attack the minerals of which rocks are composed. In every region, therefore, where rain falls, soluble rocks, such as limestone, are gradually dissolved, while other kinds of rock are decomposed and disintegrated. In limestone areas it can be shown that sometimes hundreds of feet of rock have thus been gradually removed from the surface of the land. And the great depth now and again attained by rotted rock testifies likewise to the chemical activity of rain-water. This is particularly noticeable in warm-temperate, sub-tropical, and tropical latitudes, where feldspathic rocks are not infrequently decomposed to depths of a hundred feet or more. In temperate and northern regions, the amount of rotted rock is rarely so great. The thicker rock-crusts of southern latitudes are supposed to be due to the larger supplies of acid derived from the more abundant vegetation. To some extent this is probably true, and there can be little doubt, also, that the chemical action of rain is facilitated by the higher temperature of those regions. There is another reason, however, for the relatively meagre development of rotted rock in northern countries generally. Those regions have, at a geologically recent date, been subjected to glacial conditions. Broad areas of temperate Europe and North America, for example, have been scraped bare by extensive ice-sheets, resembling those of Greenland and the Antarctic Circle. In more southern latitudes the rotted rocks have escaped such abrasion and denudation, and hence it is not strange that they should attain so great a thickness. The decomposed rock-material encountered in the northern parts of Europe and North America has been formed, for the most part, subsequent to the disappearance of glacial conditions; while in southern regions, rock decay has gone on without interruption ever since those lands came into existence.

Action of Frost.—The disintegrating action of rain in temperate and high latitudes is greatly aided by frost, and the same is the case in the elevated tracts of southern latitudes. Rain renders the superficial parts of rocks more porous, and thus enables frost to act more effectually; while frost, by

PLATE LXVIII



THE CINQUE TORRI, TYROL. [Dolomite, well bedded, breaking up along Vertical Joints.]

Photo by Photochrom Co.

[*To face page* 357

widening pores and fissures, affords readier ingress to meteoric water. Water freezing in soils and subsoils, and in the interstitial pores and minute fissures of rocks, forces the grains and particles asunder, and when thaw ensues the loosened material is ready to be carried away by rain or melting snow, and subsequently, it may be, by wind. The same process takes place on a larger scale in the prising-open of joints and bedding-planes, and the consequent rending asunder of rocks. This action is best seen in Arctic regions and at high levels in our own and other countries, where the solid rocks not infrequently become buried underneath their own ruin (Plates LXVIII., LXIX.). By and by, however, these loose, angular fragments are shattered, crumbled, and pulverised by frost, until they are in a condition to be swept away by wind, rain, or melting snow. The solid rock then comes again within reach of the same destructive action, and so the work of disruption and disintegration continues.

Action of Plants and Animals. — The acids derived from decaying organic matter are powerful agents of chemical change. Without their aid, rain would be a much less effective worker. Living plants themselves, however, attack rocks, and by means of the acids in their roots, dissolve out the mineral matter required by the organisms. Further, their roots penetrate the natural division-planes of rocks and wedge them asunder; and thus, by allowing freer percolation of water they prepare the way for more rapid disintegration. Nor can we overlook the part played by tunnelling and burrowing animals, some of which aid considerably in the work of reducing rocks. Worms, for example, by triturating in their gizzards the stony particles of a soil, reduce these in size. They also play a most important part in soil-circulation. In soils which have long been undisturbed by the plough, coarse particles and stones are usually absent. This is obviously due in chief measure to the bringing up by the worms of fine soil from below, and its deposition at the surface as "casts," which are spread out by the action of rain and wind. Eventually, in this way, a more or less considerable stratum of fine soil accumulates, and gradually buries any stones that may have been lying at the surface. It must be remembered, however, that the transport of dust by wind is also an important factor in the formation of fine soil in many regions, and that the gradual burial of "ancient monuments" of one kind or another is probably, in many cases, largely due to the gradual accretion of wind-blown materials.

Weathering of Rocks.—We have now enumerated the more important epigene agents employed in the formation of soils and subsoils. As these several agents are often associated in their work, it is sometimes hard, or even impossible, to say which has played the dominant rôle in certain cases. It is obvious, however, that the disintegration of rocks is partly a mechanical, partly a chemical, process, and that the ultimate result of superficial action is to break up minerals and rocks into soluble and insoluble, or practically insoluble ingredients. Even the hardest and most resistant of rocks and rock-ingredients must succumb. Those that resist solution are eventually reduced by mechanical action to finely divided particles, which are readily transported by running water or carried on the wings of the wind. Some of the harder minerals, and notably quartz, may long survive the rock masses of which they once formed a constituent portion, and continue to play the same part over and over again. Here, for example, is a pebble of liver-coloured quartz picked up from a gravelly beach on the Firth of Forth. Whence has it come, and what tale has it to tell? Originally it formed a portion of some vein or layer traversing the metamorphosed rocks of the Scottish Highlands. Detached from its parent rock in Old Red Sandstone times, it was rolled down the bed of some torrential stream, becoming well rounded in the process, until it reached the shore of a great inland sea—the "Lake Caledonia" of geologists. Together with many boulders and pebbles of the same kind, and multitudinous rounded stones of other types of rock, it eventually became sealed up in the great conglomerate that forms the base of the Old Red Sandstone system in Central Scotland. Ages pass away—Lake Caledonia vanishes, and its conglomerates, red sandstones, etc., and igneous rocks, now forming part of a land-surface, are gradually denuded. The old conglomerate is largely broken up, and our liver-coloured quartz, again at liberty, becomes the sport of the waves upon a sea-beach of Carboniferous times. Reduced in size by constant attrition, but otherwise unchanged, it is eventually locked up in one of the numerous conglomerates of the period. What its history may have been throughout the vast æons which succeeded up to the close of Tertiary times, we cannot tell. Possibly it lay *perdu* during all that prolonged period in its Carboniferous bed. Or it may have been dug out at some distant date, and again played its part as a rolling-stone on sea-beach or river-floor. Eventually, however, it was enclosed in the bottom-moraine or boulder-clay of the great *mer de glace* that formerly overwhelmed all Scotland. In due time this *mer de glace* vanished, leaving its accumulations to be attacked and disintegrated in their turn. Nowadays, the boulder-clay is being eaten into by the sea, and our liver-quartz, once more set free, repeats its coastal wanderings, and for all that we can tell may yet survive to run through a similar cycle of changes again and yet again.

But quartz is an exceptional mineral, in comparison with which the great majority of rock-formers are ephemeral. Few of the numerous complex silicates with which it is associated in crystalline igneous and metamorphic rocks survive the process of disaggregation by which these gradually become broken up. Now and again the feldspars, and even some of their ferromagnesian associates—all in a more or less altered state—may yet retain their individuality, and enter sparingly or more abundantly, as the case may be, into the composition of derivative rocks. In the case of *arkose*, for example, we have a rock derived immediately from the disaggregation of a granite, and consisting, therefore, of quartz, feldspar, and mica, assorted and arranged by water action. The quartz may be more or less water-worn, and the feldspar and mica not only worn but to some extent chemically altered; nevertheless, each mineral has retained its individuality. In like manner, certain of the minor accessory ingredients of crystalline igneous rocks have often survived the demolition of their parent rocks, and are now and again met with as rolled pebbles and grains in sand and gravel. In such cases, however, the gravel and sand have usually been derived directly from the disintegration of the igneous rocks in question. Neither zircon, rutile, nor magnetite could survive the manifold vicissitudes through which grains and pebbles of quartz have passed. Sooner or later they lose their individuality and are transformed.

Thus the process of rock-disintegration or "weathering," as it is termed, may be said to consist essentially in the breaking up of complex, and therefore usually unstable compounds, and the consequent production of simpler and more stable bodies. Hence, when igneous and schistose rocks are highly weathered, their complex silicates are transformed and converted into simpler compounds, some of which are soluble, while others are more or less insoluble. The soluble ingredients tend, therefore, to be leached out and washed away. The soil-cap formed upon such rocks, however, is rarely quite destitute of soluble matter. Even when the disintegrated materials have been transported by water and deposited elsewhere in the form of sand, clay, silt, etc., these sediments will usually retain a larger or smaller proportion of soluble matter; the process of disintegration and decomposition of the several constituents of the original or mother-rock has not been completed. In short, sedimentary deposits, derived directly from the breaking-up of igneous masses, frequently contain a larger or smaller proportion of the relatively unaltered detritus of the parent rocks. We know, however, that many sedimentary rocks are built up of materials which have been used over and over again. Rocks of this kind, therefore, may consist exclusively of insoluble ingredients, the only soluble matter they may contain being the binding or cementing material introduced into them by percolating water. Repeatedly exposed to weathering—winnowed and rewinnowed again and again by wind or water, or both—sedimentary materials eventually come to form beds of pure quartz-sand and fine clay, composed of hydrous silicates of alumina alone, with, in most cases, some proportion of the finest quartz-flour—all soluble ingredients having been removed.

The Soil-cap.—If the soil-cap, therefore, consists essentially of disintegrated rock-materials, it is obvious that it must vary very much in character. In some places it will contain a high percentage of soluble matter—in other places it will contain little or none at all—and between these extremes all gradations may be expected to occur. The character of the soil-cap being thus dependent upon that of the underlying rocks, a good geological map might be expected to throw much light on the present distribution of soils. And so, indeed, it does; nevertheless, other factors have had their influence upon the distribution of soils, and unless these are kept in view a geological map may be misleading. The colours upon such maps have reference, as a rule, only to the so-called "solid rocks," and these may or may not crop out at the actual surface. As a matter of fact, they are often deeply buried underneath superficial accumulations of gravel, sand, clay, loam, peat, etc. Wide regions may be represented on the map, therefore, as being occupied by limestone, or by sandstones and shales or other strata—although none of these may actually appear at the surface—the only exposures being those seen in stream- and river-courses. All the intervening low grounds may be thickly mantled with superficial deposits. In cases of this kind, therefore, the soils take their character from the overlying deposits and not from the covered and concealed bed-rock. It is hardly necessary to say that under such conditions the soil-cap may differ very considerably in character from that which the solid rocks would have yielded. Again, the actual configuration of the ground must influence the distribution of soil. All loose disintegrated rock material tends to travel downwards. Rain, alternate frost and thaw, etc., slowly or more rapidly, as the case may be, cause soil-ingredients to pass from higher to lower levels; thus the disintegrated materials derived from one kind of rock may invade and overlie the outcrops of, it may be, totally different strata. The character of a soil may even be very considerably modified by the action of the wind. In Central France, for example, wind blowing from east or south-east is laden with fine dust, derived from the disintegration of the volcanic rocks of Mont Dore and Cantal. This dust, therefore, contains many fertilising ingredients, notably potash and phosphoric acid. Brought down by rain and snow, it has appreciably increased the fertility of the soil of Limagne, each hectare of that region being estimated to receive 1000 kilos of dust per annum. But if wind in some cases adds to the growth of soil and influences its character it not infrequently operates adversely. The plateau of the Karst, between Carniola and Istria, for example, is practically devoid of soil, the strong winds constantly sweeping it away from all tracts which are not protected by forests, or sheltered by the configuration of the ground. In like manner, the mountains of Provence are denuded of soil by the mistral.

Having recognised that all soils consist of disintegrated rock materials—derived either from immediately subjacent solid rocks or from more or less incoherent accumulations, under which the latter are often concealed—some writers have classified soils as *Sedentary* and *Travelled*, or *Transported*. The terms are not strictly appropriate, but they may serve their purpose so long as we understand them to have reference to the nature and source of the materials from which the soils have been derived. It might obviate confusion, however, if we substituted the term *bed-rock soil* for *sedentary soil*, and adopted the term *drift soil* employed by our Geological Survey in place of *travelled* or *transported soil*. We should thus have two tolerably well-defined classes of soil—one including soils derived directly from the bed-rock, and the other embracing every soil formed upon the surface of unconsolidated " superficial formations " of all kinds—whether glacial, alluvial, or æolian.

1. BED-ROCK SOILS

Under ordinary conditions the soil-cap covering the bed-rock shows the following succession :—

(a) *Vegetable Soil* or *Soil Proper*. A layer of variable thickness, but seldom thinner than two or three inches, or thicker than nine or a dozen inches. Owing to the presence of organic matter it is dark in colour. It may consist of fine-grained or relatively coarse-grained materials, or of a mixture of both, its general character being necessarily determined by that of the underlying subsoil and bed-rock. Usually it is coarser in texture than the subsoil into which it gradually passes.

(b) *Subsoil*. An earthy accumulation of quite indeterminate character and thickness, but commonly finer grained and lighter in colour than the vegetable soil. Fragments of the bed-rock are usually scattered more or less abundantly through the subsoil, but are most plentiful towards the bottom of the stratum, where they often form a kind of rough rock-rubble. The subsoil proper contains no organic matter.

(c) *Bed-rock*. Just as the soil passes down gradually into the subsoil, so it is often hard to say where subsoil ends and " living rock " begins. The upper part of the latter is often much fissured, earthy matter filling the cracks until, as these are followed downwards, they close up.

The character of the disintegrated materials constituting soil and subsoil naturally depends mainly upon that of the bed-rock. Should the latter be made up of relatively insoluble ingredients—say siliceous sandstone, quartzite, serpentine, clay-slate or other argillaceous rock—the soil-cap will differ but slightly in character from the bed-rock ; it will consist simply of disaggregated rock-material which has undergone little or no chemical alteration. In such cases, the soil-cap is usually thin and meagre. On the other hand, if the bed-rock be granite or any other highly feldspathic rock, it is generally more or less deeply decomposed. The rock-fragments and particles of the soil and subsoil are likewise highly altered, the subsoil sometimes attaining a thickness of a hundred feet or more.

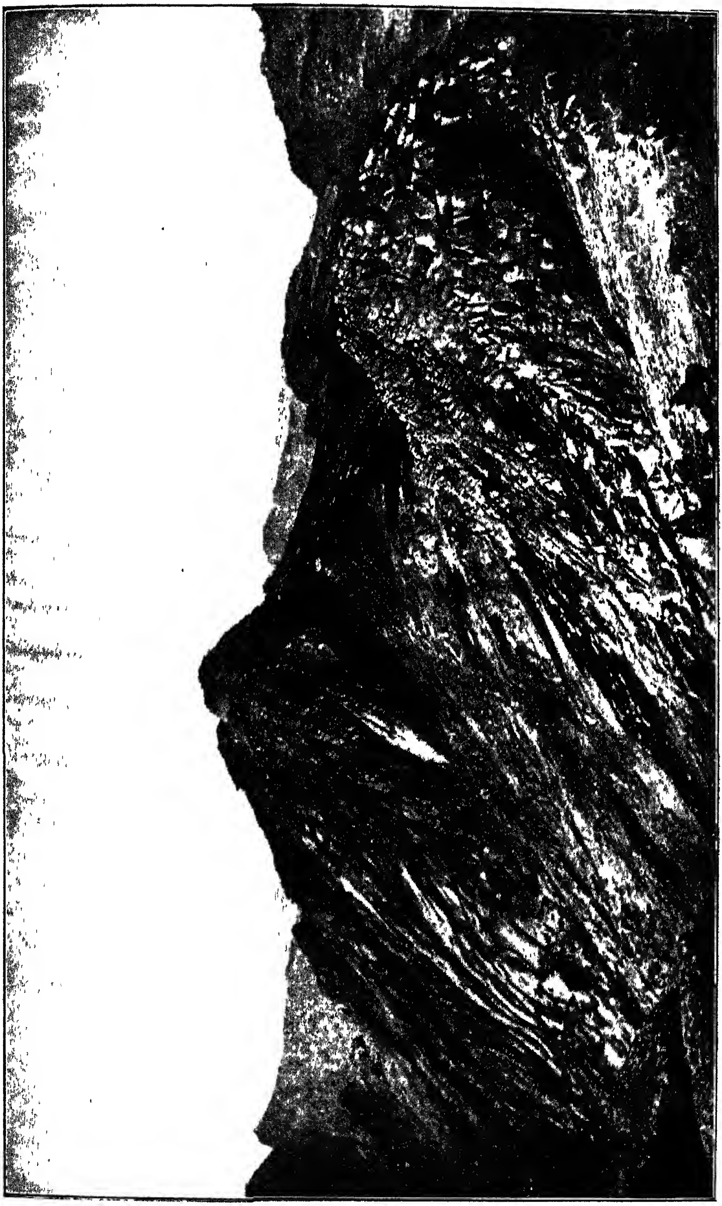
As disintegration and alteration are continually in progress, the subsoil may be said to be always gaining on the bed-rock, just as the soil continues to grow at the expense of the subsoil. The soil itself, however, does not necessarily increase in thickness, for, owing to the action of rain and wind, its surface is gradually lowered, the finer particles tending to be washed down or blown away. For the same reason, coarser grained materials become concentrated in the soil, which thus tends to acquire a coarser and more open texture than the subsoil, more especially under moist climatic conditions. The rate at which a soil wastes away varies indefinitely. Where the ground is flat and thickly clothed with vegetation, there may be little waste, while, owing to the action of worms continually bringing up fine-grained materials to the surface, the soil may come to show a finer texture than the subsoil. Other things being equal, however, surface-waste naturally increases with the slope of the ground, and is greater when the soil is bare than when it is well carpeted with verdure. As absolutely flat ground can hardly be said to exist, surface-waste is everywhere in progress, on steep and gentle slopes alike. Slowly or more rapidly, as the case may be, disintegrated rock-material is continually being urged forward, and eventually finds its way into brooks and rivers. In this way the whole surface of the land is gradually lowered. How effective such action has been, may be illustrated by the occurrence upon plateaus and flat hill-tops of rock-fragments derived from thick formations which formerly overspread those regions, but have now entirely disappeared. As an example, we may cite the " grey-wethers " or " sarsen-stones " that often occur in the soils of the Chalk Downs. These fragments of siliceous sandstone are the relics of certain Tertiary deposits, which at one time covered wide areas in southern and south-eastern England. During the slow growth and waste of the soil-cap the Tertiary deposits referred to have been gradually but persistently removed, the "sarsen-stones" (owing to their size and their insoluble character) being the only recognisable relics left behind. In this way, notwithstanding the persistence of a soil-cap through long geological ages, the whole surface of a country has nevertheless been lowered for many hundreds of feet.

The great variety of bed-rock soils may be illustrated by a short description of those met with on certain well-known types of rock.

Soils from Igneous Rocks.—The soils derived from the disintegration of igneous rocks necessarily vary in character. It will suffice, however, to cite a few typical examples.

Granite. The weathering of this rock has already been referred to, and we have learned that of its three constituents quartz is practically insoluble, while the feldspar and its ferro-magnesian associate (mica or hornblende) are more or less readily broken up and resolved into kaolin and certain alkalies and alkaline earths which tend to be washed away as bicarbonates in solution. Under favourable conditions, therefore, the subsoil overlying granite consists of an aggregate of larger and smaller roughly rounded or sub-angular fragments, in all of which the feldspar is more or less strongly kaolinised. These fragments are set in a gritty clay-like earth, usually reddish, brownish, or yellowish in colour, through which non-elastic scales of bleached mica may be plentifully scattered. Although the soluble carbonates tend to be leached out, yet a larger or smaller proportion is left behind, for the gradual decay of the rock-fragments and particles is continually setting free fresh supplies. The vegetable soil does not differ essentially from the subsoil; it is a gritty clay, often stonier than the latter, but more deficient, as a rule, in soluble ingredients, and showing few or no scales of mica.

Since granites vary in character their soil-caps are not uniformly alike. Very coarse varieties necessarily yield stonier soils than the finer grained kinds; while the resulting clays often differ much in the proportion of soluble materials. The soil derived from granites containing hornblende and a notable quantity of apatite, may be expected to be charged to some extent not only with potash and lime but phosphoric acid. Much, however, depends upon the position occupied by the bed-rock. In the low grounds of non-glaciated regions, granite is often decomposed to a very great depth, and may



Part of the Crest of Goatfell, Arran. Highly-jointed Granite breaking up under the influence of the weather.

Photo by H.M. Geological Survey.

[*To face page* 364

give a soil capable of high cultivation. But, in our own country, the rock usually occurs at mountainous elevations, where the conditions for the formation of a persistent soil-cap are not favourable. Wind, rain, and melting snow, and the steep gradients of the surface, all conspire to prevent the accumulation of disintegrated rock-materials. The hill-slopes are covered with sheets of grit and rough gravel (largely quartz); over the low grounds the clay may here and there accumulate, but the soluble materials are, for the most part, removed.

Granite may be taken as a type of the acidic feldspathic rocks. Quartz-porphyries and rhyolites yield soils of much the same character; they are essentially clays with a larger or smaller percentage of sand (quartz) and not infrequently with a notable proportion of potash, magnesia, and lime. But, just as with granite, the character of the soil-cap is largely determined by the configuration of the ground and climatic conditions. In short, the soil-cap, according to circumstances, may be a fine sandy clay, or a mere rubble of sand, grit, and rock-fragments.

Basalt. As granite is the type of the acidic igneous rocks, so basalt may be taken as representative of the basic series. The essential constituents of this rock, it will be remembered, are labradorite and augite (usually with olivine), and generally a considerable proportion of magnetite (often accompanied by ilmenite). The rock commonly weathers to some depth, becoming so disintegrated that it may be readily dug with a spade. The resulting soil is a dark-coloured loam, the more notable constituents of which are clay, fine sand, iron-oxides, and varying proportions of the carbonates of lime, potash, magnesia, together often with traces of phosphoric acid, derived doubtless from the decomposition of apatite—a common accessory mineral in basalt as in many other igneous rocks. Where the surface conditions are favourable, basalt always yields rich soils of this character.

Diorite, Andesite, etc. That large class of igneous rocks, the silica percentage of which is less than that of the granites, quartz-porphyries, etc., but larger than that of the basalts and their associates, yields soils of an intermediate character, which would be classed rather as loams than clays and are often highly fertile. The diorites and andesites are essentially compounds of soda-lime feldspars with various ferromagnesian minerals, such as hornblende, augite, biotite, etc. The rocks do not, as a rule, weather so readily as basalt; but this is not always the case, for now and again their decomposed crusts and débris can hardly be distinguished from disintegrated and decomposed basalt. Generally, however, the soil derived from these rocks of intermediate composition contains a less percentage of iron-oxide than basalt-soil, and is usually more clay-like. The subsoils, as one might have expected, are rich in lime derived chiefly from the feldspar, but also to some extent from the ferro-magnesian constituents. Other intermediate rocks as syenite, trachyte, phonolite, give subsoils that are richer in potash than lime.

Serpentine, composed mainly of relatively insoluble hydrous magnesian silicates, yields a thin soil notable for its infertility.

Upon the whole, then, we arrive at the conclusion that excellent soils may be derived from the decomposition of all igneous rocks except serpentine, some of them so argillaceous as to be properly designated clay-soils, others of a fine loamy character, and yet others of intermediate character—but all, under favourable conditions, being capable of high cultivation. The colour of the soils is lighter or darker, according as the parent rocks are poor or rich in iron-oxides. Probably, the most fertile soils are those yielded by the basic rocks (basalt, etc.), and some of the intermediate rocks (diorites and andesites), forming, as they do, dark loams, rich in the soluble ingredients required for the growth of plants.

Soils from Metamorphic Rocks.—The weathering of certain metamorphic rocks results in the formation of quite as deep and good soils as are yielded by igneous rocks generally. On the other hand, many of the schists and their associates supply only meagre barren soils. It will suffice for our purpose to note one or two examples.

Gneiss. As this rock consists usually of the same mineral constituents as granite it weathers much in the same way, and the resulting soil is similar—a gritty clay which, according to the physical conditions, may or may not be fertile. At high elevations the soil is either a mere rubble of grit and stones or a thin clay, from which the soluble constituents have usually been removed. Under more favourable conditions, as regards elevation and climate, the same rock may be covered with a deep and fertile soil-cap.

Mica-schist. This rock, composed of quartz and mica in variable proportions, often yields a good loamy soil, which in favourable positions would be highly esteemed by agriculturists. Unfortunately, in these islands it usually occurs at considerable elevations, where climatic conditions do not favour cultivation. Nevertheless, the fertility of the soil is evidenced by the character of the trees it supports — the coniferous forests grown upon the mica-schists of the Scottish Highlands being much superior in every respect to those which struggle for existence on the meagre gritty clay-soils derived from the granites and gneisses of the same region.

Hornblende-schists. These rocks are essentially aggregates of amphibole (hornblende, actinolite) and plagioclase, but many other minerals are often present. They yield dark loamy soils of excellent quality, quite similar in character to those of the diorites and basalts. The rocks, however, do not occupy large areas in Britain, and are practically confined to our mountain regions, where the conditions are unsuitable for agricultural purposes.

We have now mentioned some of the metamorphic rocks which naturally tend to yield good soils. There are a considerable number of the same group of rocks, however, which from their mineralogical composition could not be expected to supply fertile soils. Amongst these may be mentioned *clay-slate*, over which the soil is usually a cold, wet, sterile clay. Now and again, however, owing chiefly to the presence in the slate of feldspathic and micaceous ingredients, the soil may be of somewhat better quality. Another very unfavourable rock is *quartzite*, the thin soil formed upon which consists chiefly of chips, splinters, and grains of the rock held together sometimes by a meagre ferruginous sand.

Between these relatively barren soils and the good soils which, under favourable conditions, tend to form upon gneiss, mica-schist, and hornblende-schists, there are soils of intermediate character met with in many regions of metamorphic rocks, such as those that occur above *quartzose granulite*, *marble*, *chlorite-schist*, etc. The soils in question necessarily vary much in character, for the mineralogical composition of the rocks themselves is by no means uniform. The soil overlying marble is usually a clay (coloured red, brown, or yellowish, from the presence of iron-oxide), which may contain little or no trace of calcium carbonate. Marble, however, is not infrequently charged with many " new " or " contact-minerals," such as amphiboles and micas, from the gradual decomposition of which, in subsoil and soil, carbonates of lime and magnesia may be derived. Quartzose granulite, on the other hand, yields a soil comparable to that derived from the decomposition of certain gneisses and mica-schists. The soils formed upon chlorite-schist are commonly thin, gritty clays, often somewhat dark in colour, but relatively infertile, although hardly so barren as the soils derived from quartzite or clay-slate.

Soils from Derivative Rocks.—These rocks consist, for the most part, of arenaceous and argillaceous materials ; amongst them, however, are included many important calcareous rocks. No doubt there are numerous other kinds of derivative rocks ; but inasmuch as the outcrops of these occupy very limited areas, they may be here disregarded. Sandstones, shales, and limestones are by far the most widely-spread of derivative formations.

Arenaceous Rocks. The large majority of these rocks are quartzose, and they tend therefore to yield light soils which are often not sufficiently retentive. But they show great differences in this respect, many containing larger or smaller percentages of argillaceous matter, and giving rise to loamy soils of excellent quality. Some white sandstones consist almost exclusively of quartz-grains, and owe their induration to compression alone. The soil formed upon a rock of this kind, it need hardly be said, will be a barren sand, incapable of tillage. Many sandstones, however, owe their induration to some cementing material that binds the grains together. The cement may be calcium carbonate, iron-oxide, argillaceous matter, or other substance. When such rocks are weathered, therefore, the nature of the cementing material necessarily affects the character of the soil. Again, it may be noted that, although quartz is the dominant ingredient of most sandstones, yet many other constituents are sometimes present. Thus sandstones immediately derived from the breaking-up of an igneous rock may consist to no small extent of feldspar, mica, and other minerals in a more or less altered condition. Few sandstones, indeed, do not contain scales of mica, which are not infrequently so abundant as to impart a fissile structure to the rock. However plentiful these minerals may be in a sandstone itself, they are not often conspicuous in the overlying subsoil, and are usually completely wanting in the vegetable soil. It is obvious, therefore, that they must become decomposed, and that their soluble alkalies and alkaline earths are available for the support of plant-life. Some sandstones contain so much argillaceous matter that their weathered materials form clay-like rather than loamy soils. Such is usually the case with the palæozoic greywackés, which are only much indurated argillaceous sandstones. The soils they yield are usually cold, retentive clays. Owing to the fact that these rocks occur, as a rule, in high-lying districts, their soils are seldom tilled. In low-lying districts, however, soils of the same origin, when they can be well drained, are cultivated with success. Greywacké, it may be added, often contains much feldspathic material, which, on decomposing, supplies alkalies and alkaline earths.

Argillaceous Rocks. These naturally give clay-soils, but, owing to the variable character of the rocks, there are as many differences among clay-soils as among arenaceous soils. Some argillaceous strata contain so much sand, that the soil resulting from their disintegration might be classed among the loams or transition soils, being neither clays nor sands. Not a few clay rocks consist almost entirely of clay and quartz in the very finest state of division, all soluble ingredients being practically wanting. The soils formed upon these are, it need hardly be said, very infertile. Certain argillaceous rocks, on the other hand, may be largely charged with calcareous matter, and would be then termed marls, some of which yield excellent soils. It may be noted here, however, that the term *marl*, as used by some geologists, is misleading. Many of the so-called " marls " of the Old Red Sandstone, the Permian, and the Triassic systems contain no carbonate of lime, but are simply clays with a larger or smaller percentage of sand. As they occur interbedded with sandstones, the overlying soils usually assume the character of a " strong loam," forming what is one of the most fertile soils met with in these islands. Good examples are furnished by the famous " red soils " of East Lothian, Wales, and Cornwall, all of which overlie rocks of Old Red Sandstone age, and the somewhat similar soils (" red ground ") yielded by the Triassic Keuper Marl of Cheshire and the Midlands. Clay-rocks in general, however, tend to give heavy clay-soils, which are nowadays seldom tilled but kept in grass.

Calcareous Rocks. An absolutely pure limestone would be incapable of yielding a soil. All limestones, however, do contain insoluble impurities, such as sand and clay, and the soils derived from them are thus usually either loams or clays. Good examples of such soils are those met with in the Chalk districts of England. They are usually reddish or brown in colour, and vary in character from stiff, retentive clays to calcareous loams. The soil-caps of these regions are naturally thickest in the valleys, the tops and steeper slopes of the hills showing little or no soil at all. In some places, however, the hills are capped with sheets of flint-gravel, the flints having been derived from the gradual dissolution of the chalk in which they were formerly embedded. Limestones all the world over yield similar reddish, yellowish, or brownish clays and loams, the colour being due to the presence of iron-oxides. The famous *terra rossa* of Southern Europe is a well-known example. As most limestones are traversed by joints which have been widened by the action of acidulated water, much of the insoluble red earth formed at the surface is washed by rain and, in some cases, by melting snow, into these open fissures. Limestone regions, therefore, especially when relatively high, are apt to show a rocky surface, sparingly sprinkled with a thin clay-like or loamy soil.

2. DRIFT SOILS

Under this head, as already explained, may be grouped all soils which do not owe their origin to the direct disintegration of the bed-rock, but are the modified upper portions of glacial, alluvial, and æolian accumulations of every kind. The materials of which they are composed have been transported for shorter or greater distances.

Glacial Soils.—These soils are usually somewhat tenacious clays, but vary considerably in character. They overlie accumulations of glacial origin, which may consist either of stony or essentially stoneless clays, the latter being usually laminated while the former are commonly amorphous.

Boulder-clay or *Till* is the general term applied to the stony clays. These clays, being of subglacial origin, consist almost exclusively of crushed and comminuted rock. In other words, they consist of unweathered materials, differing in this respect from all clays of truly sedimentary origin. As a rule, these stony or boulder-clays are of a highly impermeable character, and consequently the soil formed upon them is usually thin. The subsoil is also thin, and the materials of which it is composed show commonly little trace of weathering, the most notable change being the partial oxidation of ferruginous constituents. Thus, a blue-coloured boulder-clay may graduate upwards into a yellowish or brownish clay, two or three feet in thickness, overlaid by a few inches of a more or less stony, tenacious clay-soil. It may be said in general terms that the colour and composition of boulder-clay are determined by the nature of the bed-rock upon which or near to which it lies. Thus, in a district where red sandstones predominate, the overlying boulder-clay is usually reddish and more or less arenaceous: where Carboniferous rocks prevail (light coloured sandstones, black shales, fireclay, ironstones, coal, limestone, etc.) the till is dull bluish-grey in colour and often exceedingly tenacious: when the dominant country-rock is chalk, the boulder-clay forms a dirty greyish-white marl. A good geological map, therefore, although it may not show the superficial formations of a country, is nevertheless often a reliable index to the average character of the boulder-clays. The general local character of the till, however, does not hold good throughout. If we follow the direction of the ice-flow in a country like Scotland, we soon discover that there are limits to the local character of the till. Coming down the valley of the Tweed, for example, from the heart of the Silurian Uplands to the low grounds near Melrose, we find that, so long as we are in the region of greywacké and shale, the till is a fawn-coloured, tenacious, gritty clay, crowded with angular and subangular fragments of the country-rock. As we leave the Silurian strata and enter the region of Old Red Sandstone, the till continues to be composed of the débris of greywacké and shale, although here and there fragments of the underlying red sandstones begin to appear. Continuing down the valley, red sandstone boulders become more and more numerous, while the colour and texture of the clay gradually change, as crushed and comminuted sandstone enters more and more largely into its composition. The majority of the stones and boulders, however, are still of Silurian parentage—doubtless due to the fact of their superior durability—the red sandstones being much more readily pulverised. The till continues to present much the same appearance after the region of red sandstone has been left behind; but gradually it loses its pronounced red colour as Kelso is approached, while fragments of certain igneous rocks, which crop to the surface above that town, begin to abound. From Kelso to the sea the prevalent rocks are brown, reddish, grey, and white sandstones, sandy shales, marls, etc. The overlying till, therefore, is a somewhat arenaceous clay, light brown as a rule, but here and there with a reddish tinge. The bulk of the finer grained materials of this till are of local origin; but the most conspicuous stones and boulders are still greywacké, commingled with abundant fragments of the "Kelso trap-rocks" and other igneous rocks traversed by the old ice-sheet. Similar phenomena are encountered everywhere in regions where boulder-clay occurs. While it is true, therefore, that this accumulation has a more or less local character—and this is especially the case with its finer grained materials—yet it must be remembered that the till formed in one place tended to travel forward with the ice. In this way boulder-clay often came to be deposited upon bed-rock of a very different character from that of the region where it was actually formed. No small proportion of the stones, and even of the gritty and clay-like material of the till that covers the low grounds of a country, is often of more or less distant derivation.

It will now be readily understood that the soils yielded by boulder-clay are of very unequal character and value. The dark lead-coloured tenacious till met with in many Carboniferous tracts gives a most ungrateful soil—a thin, cold, unctuous, sticky clay in wet weather; and in drought, hard and unyielding. In other places within the same geological area the till has proved more kindly, owing chiefly to a larger proportion of comminuted sandstone, limestone, and igneous rocks. The red and brown coloured boulder-clay soils, however, are upon the whole the best. These consist mainly of pulverised red sandstone, and form strong loams rather than clays. Chalky boulder-clays, composed chiefly of pulverised chalk, yield clay-soils from which the calcareous constituents have sometimes been largely removed.

The agricultural treatment of soils is a subject on which the geologist has no title to speak. He may, however, be allowed to point out the danger of deep-ploughing upon boulder-clay soils of all kinds. Undisturbed boulder-clay consists almost exclusively of unweathered materials; its mineral constituents are quite unaltered, and it is therefore in no sense of the term a subsoil. It plays the part, in fact, of unweathered "bed-rock." Owing to its impervious character the subsoil and soil formed upon it seldom exceed a foot or two in thickness. Now and again, as in sandstone regions, it is somewhat more pervious, and covered, therefore, with a thicker soil-cap. In some boulder-clay tracts, indeed, the arable soil considerably exceeds a foot. It will be found, however, that these thicker soils have not been derived exclusively from the boulder-clay upon which they lie, but have in large measure been washed down by rain from adjacent slopes. This is shown not only by the unusual thickness of the soil in question, but by the fact that it contains relatively few stones, while the much thinner soils of the neighbouring banks and mounds are crowded with stones, the tops of the banks being not infrequently covered with a thick sheet of coarse shingle and boulders.

Stoneless Clays. These deposits consist usually of very fine gutta-percha clays. They are generally well laminated, and are confined in these islands to maritime districts, where they seldom occur more than 130 feet above the sea-level. They are best developed in the lower reaches of the great valleys of Central Scotland, where they form a considerable proportion of the Carse-lands of the Tay, the Forth, and the Clyde. Clays of precisely the same character are met with in the Newcastle and Durham districts. The deposits have occasionally yielded shells of Arctic molluscs, and now and again an isolated stone or boulder appears: in a few places, indeed, small and large erratics are of quite common occurrence, but that is exceptional. The clays are obviously of marine origin, deposited at a time when Arctic climatic conditions obtained. When carefully examined, they prove to consist for the most part of minute particles of rock and mineral which, as a rule, are as fresh and unaltered as the similar fine ingredients of boulder-clay. When thoroughly washed and sifted, the clay yields an exceedingly fine rock meal or flour, of which the most abundant constituent is quartz. True clay or kaolin is of subordinate importance, but appears to be rather more abundant than in most true boulder-clays. These stoneless clays, therefore, would appear to be of the same origin as the former; they are the result of glacial grinding and, unlike ordinary alluvial clays, are not the product of the mechanical and chemical process of weathering. They represent the fine mud, etc., swept into our estuaries by turbid rivers escaping from large glaciers, and too short a time elapsed before they settled down, to allow of much chemical alteration. It need hardly be said that the soils met with upon such clays are peculiarly tenacious, except where, as sometimes happens, thin layers and bands of sand are intercalated in the upper part of the deposits. Deep-ploughing upon these clays is obviously not less to be avoided than in the case of true till.

Alluvial Soils.—Under this head we include all superficial deposits consisting of disintegrated and weathered rock-materials, which have been transported and spread out by water. Some of these formations have been accumulated in fresh water, others have been laid down in estuaries and upon the sea-floor. They and their soil-caps naturally vary much in character. The coarser deposits consist of water-worn shingle and gravel, and are generally barren, owing to the rapidity with which rain is absorbed. Any soil formed at the surface tends in this way to disappear. Now and again, however, when the interstices between the stones are well filled with grit and sand, a light porous soil is formed. Between such coarse accumulations and the finest deposits of mud and silt, we meet with all gradations. Of the sands, quartz is the dominant ingredient, and a pure quartz-sand, it need hardly be said, cannot furnish a good soil. Many sands, however, contain larger and smaller percentages of clay, and may form loamy soils of excellent quality. From loams capable of high cultivation, we pass on to clays, many of which are tenacious, although few alluvial clays have the tenacity so characteristic of the tills and stoneless clays of glacial origin. Alluvial clays and muds often contain much organic matter, and are frequently rich in soluble mineral salts. As examples of alluvial formations may be mentioned the flats and terraces of our river-valleys, the great Carse-lands of Middle Scotland, the raised beaches of our maritime tracts, and the many patches of level ground which indicate the sites of former lakes. Under the same head, also, we may include the fluvio-glacial heaps and sheets of gravel, sand, etc., shortly described in Chapter XX. Although these deposits are primarily of subglacial derivation, yet their materials must obviously have been more or less altered and disintegrated while they were being transported and distributed. Moreover, their highly permeable nature has allowed the free passage of rain, so that in time all such fluvio-glacial gravels and sands have acquired much the same character as the similar deposits formed by ordinary river-action.* From an agricultural point of view, therefore, they may be included under one and the same head.

In fine, it will be understood that the chief distinction between "alluvial-formations" and those which have been described under the head of "glacial soils" is simply this, that the former consist essentially of "weathered" rock-material, while the latter are composed almost exclusively of "unaltered" mineral matter—of crushed, pounded, and pulverised rock, which had previously undergone little or no chemical alteration. The "alluvial formations," in a word, consist of disintegrated rock-material, and are true "subsoils." Glacial clay-deposits, on the other hand, are not "subsoils," but, properly speaking, unaltered "bed-rock."

Æolian Soils.—The most notable æolian accumulations are the *sand-dunes* of maritime districts and certain inland areas. As the dominant ingredient of all dunes is quartz, they can hardly be said to yield a soil. Nevertheless, certain sand-loving plants find sustenance upon them, and succeed in binding the loose grains together, so that eventually some amount of humus is accumulated, and a thin soil is formed. But if æolian sand accumulations yield very poor soils, such is not the case with certain other wind-blown formations. The fine *dust* swept by the wind from desiccated regions, and distributed over adjacent tracts, may not only add to the fertility of soils, but under certain conditions may accumulate to such an extent as to conceal all bed-rock and native soil-caps over extensive areas. There can be little doubt that desert-dust has added to the fertility of the Nile Valley, while, according to Baron Richthofen, the massive sheets of *loess* which cover enormous tracts in China are true dust-deposits, gradually accumulated by the winds flowing outwards from the desiccated regions of Central Asia. In Europe, a similar deposit occurs in the Rhine Valley and in the low grounds traversed by the Danube, while the extensive sheets of "black-earth" forming the great plains of Southern Russia are also a variety of loess. The origin of the European loess has been much discussed, but it seems to be now the general opinion that the materials of the loess were, in the first place, of glacial and fluvio-glacial origin. The fine sand and clay that resulted from glacial grinding appear to have been introduced to the low grounds of Europe largely by the flooded rivers and inundations of the Ice Age. It is thought, however, that wind also played an important part in the transport of these fine-grained materials. Northern Europe covered with an ice-sheet must have formed an area of high-pressure, from which strong winds would flow southwards. During the severe winter season, all the streams and rivers would be reduced in volume, and wide areas, no longer inundated, would be exposed to the disintegrating action of frost. The fine fluvio-glacial deposits thus pulverised would be ready to be swept up by strong winds, and distributed over wide areas in Central and South-Eastern Europe. Similarly, the fluvio-glacial accumulations of the low grounds, dried and desiccated, would in like manner tend to drift before the wind. In some such way, deposits originally of glacial and fluvio-glacial origin have been rearranged and redistributed by æolian action. This conclusion is supported by the occurrence in the loess of the remains of a true Steppe-fauna—embracing jerboas, pouched marmots, tailless hare, little hamster rat, and many other forms which are the common denizens to-day of the Steppes of Eastern Russia and Western Siberia.

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* It may be noted, however, that the stones of a fluvio-glacial gravel are usually fresher than those of modern alluvial deposits. Their weathered crusts are thinner, and they are sounder internally. This is most notable in the case of basalt and similar rocks. When the stones of a modern gravel-bed have been derived directly from till, however, they are usually quite as sound as those occurring in a fluvio-glacial deposit.

Loess may be described as a fine calcareous loam, consisting of an admixture of minute particles of quartz and clay. The percentage of calcium carbonate varies, often reaching or even exceeding 30 per cent. Its light red or yellowish colour is due to the presence of iron-oxide. Small percentages of magnesia, potash, soda, and phosphoric acid are usually present. Loess thus yields an excellent soil, the regions covered by it being noted for their great fertility.

Climate and **Soil Formation.**—On limited areas, soils may be classified according to the rocks from which they have been derived, and this method has been followed successfully by Hall and Russel in their survey of the soils of Kent, Surrey and Sussex, also by Berry, Lowden and Melville in North Ayrshire. When large areas are examined, however, it is found that climate, conditioning temperature and moisture, plays a decisive part. Some soils, it is true, have not been subjected long enough to climatic influences to show the full degree of change and may be regarded as *immature*; others, especially on wide continental areas, long undisturbed, display associations of soil types with definite climatic zones, similar soils being found overlying widely different kinds of rocks. These may be regarded as *mature*.

Briefly, the soil characteristics depend on temperature and the degree of leaching by ground water. Thus, in tropical and subtropical regions with high temperature and abundant, though seasonal, rainfall, the processes at work in the soil involve rapid oxidation of the organic matter (humus), producing carbonic acid, which unites with the sodium and potassium of the mineral constituents, forming weak alkaline carbonate solutions which attack the silicates effectively. These solutions remove the silica wholly or partially, leaving a residue rich in the oxides of iron and aluminium—the sesquioxides. In this way are formed the lateritic soils so widely distributed at the present day.

In temperate regions the organic matter does not decompose so readily, the alkaline carbonates do not form, and the silica is not removed. Weak organic acids dissolve the sesquioxides and carry them to a lower level, where they are deposited, forming a readily recognised coloured layer, sometimes consolidated to form an impervious "pan." Of this kind are the "podsols," or leached soils so characteristic of the northern hemisphere.

With less rainfall and therefore reduced leaching, but with a higher temperature, a highly fertile soil is developed, marked by abundant humus, by the retention in the upper layers of the calcium carbonate, and by the removal of a part only of the alkaline carbonates and calcium sulphate. Here we may include the black and brown soils of the steppes and prairies.

In arid regions the soluble salts remain in the soil and may be brought up and concentrated at or near the surface, sometimes in such quantities as to interfere with plant growth.

The soil may be regarded, therefore, as composed of layers, some marked by removal of constituents, others by deposition, the nature of the layers being determined mainly by climate and only subordinately by the nature of the underlying rock. It is usual to call the uppermost of these the "A" horizon, the immediately underlying layer the "B" horizon, and the unaltered material beneath the "C" horizon, these three constituting the "soil profile." The study of any soil involves the examination not only of the surface but of the underlying layers. Investigation of the soil on these lines was first carried out in Russia, where the soil zones developed by climate are clearly displayed, ranging from the frozen "tundra" of the north through the leached "podsols" of the forest belt to the fertile black and brown soils of the central region and from thence to the alkaline soils of the arid districts of the south.

Soil Deterioration and Soil Erosion.—Under natural conditions a balance is usually maintained between the soil-forming processes and the agents of erosion so that the fertility of the soil is maintained for long periods. But the balance may be disturbed by adverse influences such as changing climatic conditions, failure of water-supply, waterlogging, or by wrong methods of cultivation. It has been shown recently that deterioration may set in on natural pastures as a result of overgrazing, the essential mineral constituents of the soil being drawn upon faster than they can be replaced by weathering. As a consequence the feeding value of the herbage falls and the stock maintained on the ground may become subject to deficiency diseases.

In extreme cases wholesale removal of the soil may take place with disastrous results. Erosion on this scale may be due to purely natural causes, but it has often been brought about by human agency, and chiefly by the ill-advised destruction of forests which has taken place over wide areas in many lands within comparatively recent times. In its earlier stages soil erosion attracts little notice, and, when obvious, is already far advanced and very difficult to stop. The process is commonly accompanied by other evils such as changes in the flow of streams and rivers, flooding, and failure of underground water-supplies. In extreme cases large areas may be rendered unfit for human habitation.

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APPENDICES

APPENDIX A

TABLE OF BRITISH FOSSILIFEROUS STRATA

QUATERNARY or POST-TERTIARY.	Recent (Neolithic etc.)		25 Feet and 50 Feet Raised Beaches; Blown Sand; Lacustrine and Fluviatile Deposits; Bogs or Peat-Mosses; Moraines, etc.
	Pleistocene (Palæolithic)		100 Feet Raised Beach; Glacial and Interglacial Deposits.
CAINOZOIC or TERTIARY.	Pliocene	NEWER	Cromer Forest-bed Group. Weybourn and Chillesford Crags. Norwich Crag. Red Crag.
		OLDER	St Erth Beds; Coralline Crag; Lenham Beds, etc.
	Miocene		(Wanting in Britain.)
	Oligocene		Hamstead Beds. Bembridge Beds. Osborne or St Helen's Beds. Headon Beds.
	Eocene	UPPER	Headon Hill Sands; Barton Clay; Upper Bagshot Sands.
		MIDDLE	Bracklesham Beds and Middle Bagshot Sands.
		LOWER	Lower Bagshot Sands. London Clay and Bognor Beds. Oldhaven Beds. Woolwich and Reading Series. Thanet Sand.
MESOZOIC or SECONDARY.	Cretaceous	UPPER	Upper Chalk. Middle Chalk. Lower Chalk and Chalk Marl. Upper Greensand. Gault.
		LOWER	Lower Greensand. Weald Clay. Hastings Sand.
	Jurassic	UPPER or PORTLAND OÖLITES.	Purbeck Beds. Portland Beds. Kimeridge Clay.
		MIDDLE or OXFORD OÖLITES.	Coral Rag. Oxford Clay.
		LOWER or BATH OÖLITES	Cornbrash and Forest Marble. Great or Bath Oölite, with Stonesfield Slate. Fuller's Earth. Inferior Oölite.
		LIAS	Upper Lias. Middle ,, Lower ,,

MESOZOIC or SECONDARY.	**Triassic**	Rhætic	Penarth Beds.
		Upper or Keuper	New Red Marl. Lower Keuper Sandstone.
		Middle	(Wanting in Britain.)
		Lower or Bunter	Upper Mottled Sandstone. Pebble Beds. Lower Mottled Sandstone.
PALÆOZOIC or PRIMARY.	**Permian**	Upper	Red Sandstones, Clays, etc. Magnesian Limestone. Marl Slate.
		Lower	Red Sandstones, Clays, Breccias, and Conglomerates.
	Carboniferous	Coal-Measures	Red Sandstones, and Upper Coal-bearing Series. Middle Coal-bearing Series. Lower Coal-bearing Series ("Ganister Beds").
		Millstone Grit	Thick Sandstones, etc.
		Carboniferous Limestone	Yoredale Beds. Main or Scaur Limestone. Lower Limestone Shale (England), and Calciferous Sandstones (Scotland).
	Devonian and Old Red Sandstone		Upper Devonian and Old Red Sandstone. Middle Devonian and Old Red Sandstone. Lower Devonian and Old Red Sandstone.
	Silurian		Downton and Ludlow Group. Wenlock Group. Llandovery Group.
	Ordovician		Bala and Caradoc Group. Llandeilo Group. Arenig Group.
	Cambrian	Upper	Tremadoc Slates. Lingula Flags.
		Middle	Menevian Group.
		Lower	Harlech and Llanberis Group.
	Archæan and Pre-Cambrian		Torridon Sandstones, etc. Lewisian or Fundamental Gneiss.

APPENDIX B

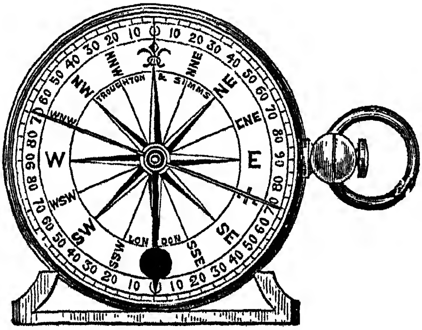
MOHS' SCALE OF HARDNESS

1. Talc.
2. Gypsum.
3. Calcite.
4. Fluor-spar.
5. Apatite.
6. Orthoclase.
7. Quartz.
8. Topaz.
9. Corundum.
10. Diamond.

APPENDIX C

COMPASS AND CLINOMETER

Any ordinary pocket-compass, if not too small, will serve to take the direction of dip. The one in common use by field geologists is divided into graduated quadrants. From North and South points, the figures in each quadrant run up on either side to 90°. In taking an observation, allowance must be made for the declination or variation—magnetic north in these islands, at the present time, being about 14° west of true north. As all maps are constructed with reference to the true meridian, it is necessary that the dip-arrows we insert should likewise indicate true and not magnetic directions. In recording an observation of dip, we say that the direction is so many degrees west of north, east of south, north of west, and so on, as the case may be. Thus N. 25° W. means 25° west of north.



Not infrequently, owing to the absence or paucity of streams, roads, fences, buildings, etc., the geologist may sometimes have difficulty in locating the position upon the map of some outcrop or other field data, which he desires to indicate. In order to do so he must of course take bearings with the compass, for which purpose such an instrument as that shown in the accompanying illustration is usually sufficient, but if great accuracy be demanded a prismatic compass will be necessary. After some little practice, however, the observer will find an ordinary pocket-compass quite good enough for all his requirements.

In the combined compass and clinometer here illustrated a pendulum hangs perpendicularly from the central point which carries the needle, and indicates the number of degrees the straight-edge or base attached to the side, deviates from the horizontal. In the illustration the base being level, the pendulum points to zero. One advantage of this little instrument is that the straight-edge can be applied either to the upper or under side of a bed. Or if we are taking the angle of dip from a little distance, and holding the instrument between the eye and the angle to be measured, it is obviously immaterial whether the straight-edge occupies the position shown in the illustration or is inverted.

INDEX

ABERDEENSHIRE, 222
Abyssal eruptive rocks, 188
Abyssinia, 54
Accessory minerals of igneous rocks, 37, 38
Acid igneous rocks, 39
Acmite, 20
Actinolite, 18; -schist, 87
Ægirine-augite, 20
Ægirine-syenite, 47; -trachyte, 49
Æolian rocks, 62, 64; soils, 375
Agate, 5
Agglomerate, volcanic, 60, 209; -dykes, 209
Alabaster, 30, 72
Albite, 12, 13; -schists, 230
Alderley Edge, ores at, 260
Alkali-granites, 42; -syenites, 47; -trachytes, 49
Allivalite, 52
Alluvial clay, 67; soils, 374
Almandine, 24; -zone, 228
Alps, 169, 177, 300
Alteration of rocks, 38, 217, 358
Alum-shale, 68
Amber, 93, 102
Amethystine quartz, 5
Amianthus, 18
Amphibole group, 17, 228
Amphibolite, 87
Amygdales, 125, 126
Analcite, 15; -basalt, 57; -basanite, 57; -phonolite, 56; -syenite, 55; -theralite, 56
Analcitite, 57
Andalusite, 26; -hornfels, 90, 219, 221
Anderson, E. M., 207
Andesine, 12, 13
Andesite, 49, 50, 207, 209; -tuff, 60; soils derived from, 365
Anhedral (xenomorphic) minerals, 35
Anhydrite, 30
Animal-tracks, 119
Animals, geological action of, 357
Anorthite, 12, 13, 222
Anorthoclase, 12
Anorthosite, 52
Anthophyllite-schist, 230
Anthracite, 78
Anticlines, 135
Anticlinorium, 140
Antigorite, 23
Antrim, plateau-basalts of, 216
Apatite, 31, 81; veins of, 223, 262
Apennines, 300
Aphanitic, 35
Aplite, 43, 55; -veins, 204
Aplogranite, 42
Aqueous rocks, 61
Aragonite, 29
Arctic plant- and animal-remains in Pleistocene, 99, 310, 311
Ardnamurchan, 205, 206, 207
Arenaceous rocks, soils from, 368
Arfvedsonite, 19; -granite, 42; -trachyte, 49
Argillaceous rocks, concretionary, 124; soils from, 369
Arkose, 67, 359
Arran, 44, 199, 207
Artesian Wells, 347; conditions for, 350
Asbestos, 18
Ash, 59
Assimilation of rocks, by granite, etc., 193, 222
Association of ores in lodes, 250
Assynt, 55
Augen structure, 230
Augite, 20; -andesite, 51; -diorite, 50; -peridotite, 58; -syenite, 47
Aureole, metamorphic, 220
Auriferous deposits, 237
Autogenous veins, 203, 204
Avanturine, 5
Ayrshire, 209

BACK of lode, 248
Bailey, E. B., 115, 174, 204
Balas-ruby, 8
Ball-and-socket joints, 149
Banded lodes, 246
Banket (S. Africa), 261

Barkevikite, 19
Barren ground in faulted strata, 156
Barrow, George, 228
Barytes, 30
Basalt, 53, 209; joints in, 148, 202; soils derived from, 365; -tuff, 60; weathering of, 150
Basaltic hornblende, 19
Basanite, 40, 56
Basic igneous rocks, 39
Basin in valley of Rhine above Bingen, 179
Bastite, 21
Batholiths, 190; metamorphic effects of, 221
Bed or stratum, 109; lenticular form of, 112
Bedded veins, 238, 255
Bed-rock soils, 362
Beds, extent and termination of, 111
Bendigo Goldfield, 255
Ben Nevis, 51, 204
Biotite, 16; -andesite, 51; -diorite, 49; -gneiss, 87; -granite, 42; -granulite, 88, 229; -pyroxenite, 58; -schist, 85; -syenite, 47; -trachyte, 49; -zone, 228
Bismuth ores, 250
Bitter spar, 29
Bituminous rocks, 79
Blaafjeld, Norway, 234
Blackband ironstone, 30, 74
Black-earth of Russia, 376
Blatt, 169
Blocks, volcanic, 59
Bloodstone, 5
Blown sand, 64
Bog iron-ore, 73
Bohnerz, 257
Bombs, volcanic, 59
Bornite, 250
Borolanite, 55
Bosses, 190, 192
Bostonite, 47
Botryococcus, 80
Boulder-clay, 69, 302, 334, 370
Braid Hills, 49
Branching lodes, 243
Breaks in succession, 184
Breccia, aqueous, 66; crush or friction-, 91, 168; scree-, 63; volcanic, 60
Brecciated lodes, 247; rocks near plutonic masses, 203, 263
Brick-clay, 68; -earth, 63
British Columbia, 234
Bronzite, 20
Brucite-marble, 89
Bunches of ore, 258
Bytownite, 12, 13

CAIRNGORM, 5
Calc-alkali-granites, 42; -syenites, 47; -trachytes, 49
Calcareous concretions, 122, 124
Calcareous rocks, 70, 94, 125; soils derived from, 369
Calcite, 29; -schists, 229
Calc-silicate-hornfels, 90
California, placers of, 237
Canary laurel, 99
Cannel-coal, 79
Carbon, 31
Carbonaceous limestone, 71; -rocks, 77; -shale, 68
Carbonates, 29
Carboniferous Limestone, 117, 146, 182; sills, 56, 57, 196; System, ores of, 236, 258
Carbonisation of fossils, 93
Carinthia, ore-formations of, 259
Carlingford, 207
Carlsbad twin, 11
Carnelian, 5
Carpathians, 263
Carse-clays, 373, 374
Cassiterite-veins, 223
Casts (fossils), 93
Cataclastic rocks, 90, 224, 226; structure, 84
Celadonite, 23
Centroclinal fold, 134
Ceylonite, 7
Chabazite, 27
Chablais, 177
Chalcedony, 5
Chalcopyrite, 28, 233, 234, 250
Chalk, 75, 82
Chalybite, 29
Chamosite, 74
Charnockite, 41
Chemically-formed rocks, 70
Chert, 6, 73, 121; radiolarian-, 76; sponge-, 77
Cheviot Hills, 51, 209
Chiastolite, 26; -slate, 86
China-clay, 68
China-clay rock, 42
Chlorite, 22, 228; -zone, 228
Chlorite-schist, 85, 86, 230; soils derived from, 367
Chloritoids, 228
Christmas Island, 82

Chromite, 7, 58, 59, 233, 234
Chromitite, 59
Chrysolite, 21
Chrysoprase, 5
Chrysotile, 23
Clarain, 78
Classification of crystalline igneous rocks, 39
Clastic ore-formations, 236
Clay-ironstone, 30, 74, 123, 236
Clays, 67, 370, 373
Clay-slate, 85; soils derived from, 367
Cleat, of coal, 146
Cleavage, of minerals, 2
Cleavage. *See* Slaty-cleavage
Climate, influence on soil-formation, 376
Climatic conditions deduced from fossils, 99
Clinometer, 127, 271, 381
Clinozoisite, 24
Clough, C. T., 204
Coal, 77; coked by igneous rock, 149; joints in, 146; origin of, 78, 79; search for, 321
Cobalt ores, 250, 260
Cocardenerze (Cockade ores), 248
Coincident lodes, 242
Coke, 149
Collet, L. W., 169
Colorado Plateau, 178
Columbia River, 215
Columnar joints, 147
Comby lodes, 247
Common Hornblende, 19
Common Wells, 345
Compass, 127, 271, 381
Complex faults, 165
Complex lodes, 241
Composite dykes, 202; sills, 198
Compression, flow of rocks under, 142; unilateral, 141
Comstock lode, 251
Concordant injections, 190, 194
Concretions and concretionary structures, 71, 121, 235
Cone-sheets, 190, 204, 206, 207
Conformity, 182
Conglomerate, 66, 95; auriferous, 260; crush-, 226; distortion of, 143; friction-, 91, 168
Consolidation of incoherent accumulations, 106
Contact metamorphism, 219, 223
Contact minerals, 221, 367
Contact ore-formations, 262
Contaminated gabbros, 222
Contemporaneous erosion, 112
Contemporaneous igneous rocks, 213
Contemporaneous ore-formations, 232
Contemporaneous veins, 204
Contents of fissure-veins, 246
Contorted strata, 142
Contraction, a cause of jointing, 150
Convergent lodes, 243
Copper, 233, 261; ores of, 250, 252, 257, 260, 326
Coprolites, 94
Cordierite, 26, 222; -gneiss, 87; -hornfels, 90, 221; -slate, 86
Cornstone, 71
Cornwall, ores of, 237, 252
Corroded minerals in igneous rocks, 36
Corsica, 50
Corsite, 50
Corstorphine, G. S., 261
Corundum, 9, 221
Country-rock, 239
Crag-and-tail, 305
Crosby, W. O., 153
Cross-bedding, 113
Cross-galleries in coal-mines, 146
Cross-joints, 147, 152
Cross-veins, 245
Crush-breccia, 91, 168
Crustal flexures, 143
Crustal movements, slowly effected, 178; a cause of jointing, 152
Cryptocrystalline structure, 37, 43, 45, 46
Crystalline igneous rocks, 34
Crystalline metamorphic rocks, 83
Crystallites, 35
Cubic crystals, 2
Cumberland, ores of, 258, 266
Cumming, G. A., 169
Current-bedding, 114
Curvature of strata, 127, 132
Cyanite. *See* Kyanite

DACITE, 40, 45, 46
Dacitic obsidian, 46; pitchstone, 46
Daly, R. A., 45, 193
Danube River, 375
Daubrée, A., 153
David, Sir E., 80
Deccan, 54, 216
De-dolomitisation, 89, 222
Deep leads, 237
Deflation, 64, 355
Deformation of crust, slowly effected, 178
Deltas, 114
Dendrites, 123
Dent Blanche, 177

Denudation, 191, 251. *See also* Erosion
Depth of lodes, 240
Derivative rocks, 61; soils from, 368
Desquamation of rock-surfaces, 151, 355
Devitrification, 37
Diabase, 53
Diagonal-bedding, 113
Diallage, 20, 52; -hypersthene-pyroxenite, 58; -peridotite, 58
Diallagite, 58
Diatomaceous chert, 77; -earth, 77; -ooze, 77
Diatomite, 77
Dichroite, 26. *See also* Cordierite
Diopside, 20; -marble, 89
Diorite, 40, 49; orbicular-, 50; soils derived from, 365
Dip, 127, 271, 274, 285, 381
Dip-faults, 157
Dip-joints, 146
Dip-slope, 290
Dirt-bed of Portland, 102
Disconformity, 183
Discordant injections, 190, 199
Disintegration of rocks, 354
Dislocations. *See* Faults
Disseminations, 260
Divergent lodes, 243
Dolerite, 51, 52, 207
Dolomite (mineral), 29; (rock), 71, 124; -marble, 89
Dolomitic Limestone, 71
Double-fold, 174
Downcasts, 155
Downthrows, 155
Drainage, natural underground, 338; sewerage-, 351
Drift soils, 362, 370
Driven Wells, 346
Drumlins (Drums), 303, 308, 309
Druse and Drusy Cavities, 37, 41, 125, 247
Duluth, Lake Superior, 198
Dunes, 64, 113, 375
Dunite, 58
Durain, 78
Dust, 65, 355, 361, 375
Dutch East Indies, 57
Dykes, 190, 199, 209, 210, 216, 294; composite- and multiple-, 202; effect on underground circulation of water, 343; ring-, 204; swarms of, 199
Dynamic metamorphism, 219, 224
Dynamothermal metamorphism, 219, 227

EARTHQUAKES, a cause of jointing, 153
East Africa, 57, 80
Eclogite, 19, 59, 231
Economic geology, 321
Effusive eruptive rocks, 39, 213
Eildon Hills, 49
Elaeolite, 14, 55
Elements, 31
Elk Mountains, laccoliths of, 194
Embankments, foundations of, 337
Emery, 9
Enclosures in minerals, 5, 6
End, of coal, 146
Endogenous veins, 203, 204
Endomorphs, 6
Engineering and geological structure, 329
Enstatite, 20, 21
Enstenite, 20
Eocene, climate of, 100; contrast between deposits of, in London Basin and in Switzerland, 108
Epidote group, 23, 228
Epigene action, 61, 217, 354
Epigenetic ore-formations, 232, 238
Equipment for field-work, 269
Erosion, contemporaneous, 112. *See also* Denudation
Eruptive rocks, structure of, 188, 208; mapping of, 293
Erzgebirge, 251, 263
Escarpments, 181, 290
Eskers, 306
Essential minerals of igneous rocks, 37, 38
Eucrite, 52
Euhedral (idiomorphic) minerals, 35
Excavations, 329
Exfoliation, of basalt, etc., 150, 152
Exogenous veins, 203
Expansion, a cause of jointing, 151
Explanatory Memoirs, 312

FACE, of coal, 146
Fairy-stones, 123
False-bedding, 114
Fan-shaped structure, 140
Fault-breccia (fault-rock), 90, 156
Faults, 154, 289, 292; influence of, on underground circulation of water, 343; origin of, 171; shifting of, 166
Fayalite, 21
Feldspars, 9
Feldspathic rocks, 40
Feldspathoidal rocks, 40
Feldspathoids, 13
Felsite, 44, 205, 207, 209
Ferruginous concretions, 122
Fibrolite, 26
Field-equipment, 269

Field geology, 268
Fife, 209, 214
Fingal's Cave, 148
Finland, 45, 233
Fire-clay, 68
Fissure-veins. *See* Lodes
Fissures, nature of, 239
Fissures of contraction, 253
Fixed constituents, of magmas, 264
Flagstone, 67
Flaser-gabbro, 52
Flats, 253, 255, 258
Flaw, 169
Flexures, monoclinal, 133, 172, 173. *See* Curvature of strata
Flint, 6, 72, 121
Flinty-crush rock, 91, 227
Flow of rocks under pressure, 142
Fluidal structure, 36, 43
Fluorite (Fluor-spar), 27, 250
Fluviatile deposits, 309
Fluvio-glacial deposits, 301, 375
Fluxion-foliation, 83
Fluxion structure, 36, 37, 45, 46
Fold-faults, 174
Folds, centroclinal, 134; contorted, 142; inclined or asymmetrical, 137, 174, 226; isoclinal, 138; normal or vertical, 134; quaquaversal, 134; recumbent, 139
Foliation, 83, 228
Foot-wall, 239
Forest-beds in peat, 311
Form of ground and its relation to geological structure, 280, 289
Forsterite, 21; -marble, 89
Fossiliferous strata, Table of, 379
Fossils, 92; chiefly marine, 96; climatic conditions deduced from, 99; crustal movements deduced from, 103; geographical conditions deduced from, 101; geological chronology dependent on, 103; importance of, in geological investigations, 99; rocks in which they occur, 94
Foundations in relation to geological structure, 333
Fragmental igneous rocks, 59, 215
France, North, former genial winters in, 99
Freestone, 67
Friction-breccia, 91, 168
Friction-conglomerate, 91, 168
Frost, action of, 62, 69, 356
Fugitive constituents of magmas, 264
Fuller's earth, 68
Fusain, 78
Fusion of granitic layer of crust, 193

GABBRO, 40, 51; orbicular-, 52
Galena, 246
Gangue, 246
Garleton Hills, 49
Garnet, 24, 221, 222; -amphibolite, 231; -biotite-schist, 85; -gneiss, 231; -granulite, 88; -zone, 228
Gas-coal, 78
Gash-veins, 258
Geanticline, 143
Geer, G. de, 116
Geikie, Sir A., 216
Geikie, J. Somerville, 263
Geode, 125, 126
Geological maps and sections, 273, 312, 315
Geological structure, economic aspects of, 321, 335
Geological surveying, 268
Geosyncline, 143
Geyserite, 6
Giant granite, 42
Giant's Causeway, 148
Gilbert, G. K., 194
Glacial rocks, 69, 301
Glacial soils, 370
Glacial striæ, etc., 304
Glacier lakes, former, 307
Glacio-aqueous clay, 68
Glarner region, 174
Glass in igneous rocks, 35, 37
Glauconite, 23, 67
Glaucophane, 19
Glen Coe, 44, 51, 204
Gneiss, 85, 87, 221, 229, 231; soils derived from, 366
Gold, 28, 233, 236, 237, 251, 256, 260, 263, 265, 266
Goldschmidt, V. M., 228
Goroblagodat, contact ore of, 263
Gossans, 249, 266, 324, 326
Graded-bedding, 115
Grain of granite, 152
Granite, 40; batholiths of, 191; grain of, 152; joints in, 147; rift of, 152; secretions in, 126; soils derived from, 364; xenoliths in, 42, 192
Granite-gneiss, 42
Granitoid structure, 37, 41
Granoblastic rocks, 87; structure, 84, 224
Granodiorite, 40, 44
Granophyre, 43, 207
Granophyric structure, 41

Granulite, 88, 222, 229, 231; soils derived from, 367
Graphic granite, 41, 42
Graphite, 31; -schist, 85, 228
Gravel and Sand, mounds of, 306
Great Crustal Flexures, 143
Great Glen fault, 169
Great Oölite, ores of, 236
Greenalite, 23
Greensand, 67; iron-ores in Lower, 236; sponge-cherts of Lower and Upper, 77
Greisen, 42
Greywacké, 67; soils derived from, 369
Grey-wethers, 363
Grit, 66
Grossularite, 24
Groundmass, 35, 36
Grout, F. F., 198
Guano, 82
Gypsum, 30, 72; concretions of, 123

HADE of faults, 154, 168; of lodes, 239
Hæmatite, 6, 73, 258, 259
Haloids, 27
Hammers, geological, 269
Hanging-wall, 239
Hardness, scale of, 380
Harker, A., 198, 207, 224
Harz Mountains, ores of, 263
Hatch, F. H., 261
Haüyne, 15; -phonolite, 56
Hawaii, 54
Heave, of faults, 155, 157
Heavy spar, 30
Heliotrope, 5
Hemicrystalline igneous rocks, 37
Henry Mountains, laccoliths of, 194
Heulandite, 27
Hexagonal crystals, 2
Himalayas, 178
Holland, iron-ores of, 235
Holocrystalline igneous rocks, 37
Horizontal or profile sections, 315
Hornblende, 18; -andesite, 51; -diorite, 49, 222; -gneiss, 87, 230; -granite, 42; -peridotite, 58, 222; -schist, 87, 229, 230, 367; -syenite, 47
Hornblendite, 59
Horne, J., 292
Hornfels, 89, 221
Hornstone, 6, 73
Horst mountains, 182
Household coal, 78
Hungary, 44, 251
Hutton, James, 230
Hyacinth, 25
Hyalite, 6
Hyalopilitic structure, 51
Hydro-hæmatite, 7
Hydrothermal origin of minerals, 38; phase of ore-deposition, 265
Hypabyssal eruptive rocks, 39, 188
Hypersthene, 20; -andesite, 51; -basalt, 54; -diorite, 50; -dolerite, 53; -gabbro, 52; -granulite, 222; peridotite, 58; -pyroxenite, 58
Hypersthenite, 58
Hypidiomorphic (subhedral) minerals, 35; -granular structure, 37
Hypocrystalline groundmass, 37

ICELAND, plateau-basalts of, 54, 216
Idiomorphic (euhedral) minerals, 35
Igneous rocks, classification of, 34, 39, 40; general characters of, 34, 59; geological structure of, 188, 208; mineral ingredients of, 37; ores in, 233; secretions in, 125; soils derived from, 364
Ilmenite, 8, 233
Ilmenitite, 59
Imbricate (schuppen) structure, caused by faults, 176
Imbricated structure of sedimentary rocks, 307
Impounded streams, 335
Impregnations, 253, 257, 259
Inclination of strata, 127
Inclined folds, 137
Inclined sheets, 207
Inclusions in minerals, 5, 6
Incrustation, of fossils, 93
Index-beds, 282
Infusorial Earth, 77
Injected masses, 190
Injection-plexus, 204
Inliers, 181
Inner Hebrides, 54
Insolation, 62, 64, 151, 355
Interbedded igneous rocks, 213
Intermediate igneous rocks, 39
Intersection of faults, 167; of lodes, 243
Intervals indicated by planes of bedding, 110
Intratelluric stage of consolidation, 36
Intrusive rocks, 188
Inversion, 138
Iolite, 26
Iron-hat, 249, 250. *See* Gossans
Iron ores, 233, 234, 235, 236, 238, 250, 257, 258, 259, 263

Ironstones, 73
Irregular ore-formations, 257
Isle of Man, 226
Isoclinal folds, 138
Isometric crystals, 2
Italy, ores of, 234

JADE, 18
Japan, 263
Jargon, 25
Jasper, 6; radiolarian-, 76
Jasp-opal, 6
Joints, 144; in bedded rocks, 145; influence of changes of temperature upon, 145; in igneous rocks, 147, 202, 211; in schistose rocks, 149; origin of, 150
Jura, 169

KAMES, 306
Kankar, 123
Kaolin, 27, 68
Kaolinite, 27, 68
Keeweenaw Point, copper of, 261
Kendall, J. D., 259
Kennedy, W. Q., 169
Kentallenite, 47
Keratophyre, 49
Kerogen, 80
Kersantite, 50
Kidney-ore, 7
Kieselguhr, 77
Klapperstein, 122
Klippes, 174, 177
Knotted slate, 86
Kyanite, 26, 227; -gneiss, 229; -granulite, 88; -zone, 228

LABRADORITE, 12, 13, 51
Laccoliths, 190, 194, 198
La Celle, tufa of, 99
Lacroix, A., 222
Lacustrine deposits, 309
Lag, 175
Lake Caledonia, 358
Lake Superior, copper at, 261
Lakes, 335
Lamellated lodes, 246
Lamination, 108; diagonal-, 113
Lamplugh, G. W., 226
Lamprophyric differentiates, 47, 48, 50, 57
Landscape-marble, 124
Lapilli, 59
Lapworth, C., 227
Larvikite, 47
Laterite, 63
Layers, 109
Leached guano, 82
Lead ores, 250, 257, 259, 326
Leaf-by-leaf injection, 192
Lee-seite, 305
Lens, 270
Leucite, 14; -basalt, 57; -basanite, 57; -phonolite, 55; -syenite, 55; -tephrite, 57; -trachyte, 55
Leucitite, 57
Leucitophyre, 56
Leucoxene, 8, 25
Level-course in coal mines, 146
Lewis, F. J., 311
Lias, 117, 236
Lignite, 78, 322
Limburgite, 59
Limestones, 71, 75, 76; replaced by hæmatite, 259
Limonite, 7, 73, 235, 257
Lipari Islands, 43, 44
Liparite, 43
Lithoidal, 35
Lithomarge, 27
Liver-quartz, 358; -rock, 67
Loam, 69, 365, 366, 368, 369, 370, 372, 374, 376
Loch Ba, Mull, 205
Loch Ness, 317
Lodes, 239; association of ores in, 250; bedded, 255; branching and intersecting, 243; coincident and transverse, 242; contents of, 246; depth of, 240; hade or underlie of, 239; heaving of, 245; massive, 246; outcrop of, 248; simple and complex, 240; structure of, 246; succession of minerals in, 250; systems of, 242; walls of, 252; width and extent of, 240
Loess, 65, 375; concretions in, 123
London-clay, fossils of, 100
Longitudinal faults, 158
Lopoliths, 190, 198
Lower Greensand, ores of, 236
Lower Oölite, 117
Lustre of minerals, 2
Luxulyanite, 42
Lydian-stone, 73

MACGREGOR, M., 292
Macroscopic (megascopic) characters, 1
Magmatic segregation of ores, 264
Magmatic stoping, 193
Magnetic Pyrite. *See* Pyrrhotite
Magnetite, 7, 38, 233

Magnetitite (Magnetite-rock), 59
Magnesian Limestone, 72
Malachite, 260
Malaysian tin-fields, 237
Manganese concretions, 123; -ores, 235, 236, 238, 260, 266, 326
Maps, 272
Marble, 89, 221; soils derived from, 367
Marcasite, 28, 123
Marl, 76, 369
Marlekor, 123
Marr, J. E., 169
Masses (ore-formations), 257
Massive lodes, 246
Master-joints, 145
Matrix, in lodes, 246
Matterhorn, 177
Maufe, H. B., 204
Measurement of thickness of strata, 286
Mechanically-formed rocks, 62
Meerschaum, 22
Meinkjär, Norway, 235
Melanite, 24, 54, 55, 57
Memoirs, explanatory, 312
Mendip Hills, Carboniferous Limestone of, 117
Menilite, 6, 122
Mer de glace, 304
Mesozoic iron-ores, 236
Metals as rock-constituents, 233
Metamorphic rocks, 83; soils derived from, 366
Metamorphism, 218, 296
Metasomatic replacement, 258
Mexico, gold and silver lodes of, 263
Miarolitic cavities, 37
Mica, 16; -schist, 85, 366; -trap, 48, 50
Microcline, 11; soda-, 12
Microcrystalline, 37
Microdiorite, 49, 50
Microfoyaite, 55
Microgranite, 40, 42
Microgranodiorite, 45
Microlites, 35
Microsyenite, 46, 47
Minerals, rock-forming, 3; inclusions in, 5, 6; in igneous rocks, 37; physical characters of, 2; primary, 37, 38; replacing organic structures, 94; secondary, 37, 38, 39
Minette, 48
Mohs' Scale of Hardness, 380
Molecular replacement, 94
Molybdenite, 250
Monchiquite, 57
Monoclinal flexures and faults, 172, 173
Monoclines, 133
Monoclinic crystals, 2
Monte Nuovo, 208
Monzonite, 47
Moraines, 69, 306
Morion, 5
Moss-agate, 5
"Mother Lode," Sierra Nevada, 240, 263
Mottram St Andrews, ore at, 260
Moulds and casts (fossils), 93
Mountain-cork, 18; -leather, 18
Mountain structure, simple types of, 141
Mourne Mountains, 207
Mull, 199, 204, 207, 216
Multiple dykes, 202; -sills, 198
Muscovite, 16, 17, 66, 228; -biotite-granite, 42; -schist, 85
Mylonite, 90, 227
Mythen, 177

NÄKKEBRÖD, 123
Napoleonite, 50
Nappe, 174; -outlier, 174
Native metals in igneous rocks, 233
Natrolite, 27
Necks, 208, 294; origin of, 211
Nepheline, 14; -basalt, 57; -basanite, 57; -microsyenites, 55; -syenite, 54; -syenite-aplite, 55; -syenite-porphyry, 55
Nephelinite, 57
Nephrite, 18
Nests, of ore, 258
New Zealand, 58, 233, 263
Nickel-iron, in igneous rocks, 233
Nickel ores, 250, 326
Nile Valley, 375
Noble Serpentine, 23
Nodules, 121
Nordmarkite, 47
Norite, 52, 222
Normal faults, 154, 171, 289, 298
Normal folds, 134
Norway, ore-formations of, 233, 234, 238, 263; rocks of, 47, 55
Nosean, 15
Note-book, geological, 271

OBLIQUE bedding, 113; faults, 163
Obsidian, 44, 46
Ocean Island, 82
Ochil Hills, 51, 215
Oil-shale, 80
Old Red Sandstone, 44, 49, 51, 146, 204, 369
Oligoclase, 12, 13, 49

Olivine, 21; -analcitite, 57; -basalt, 54; -dolerite, 53; -eucrite, 52; -gabbro, 52; -leucitite, 57; -nephelinite, 57; -norite, 52
Omphacite, 19
Onyx, 5
Oölite, 71, 75; Lower, of England, 117
Oölitic iron-ore, 73, 257
Opal, 6
Ophicalcite, 89
Ophitic structure, 52
Orbicular structure, 37; -diorite, 50; -gabbro, 52; -granite, 42; -norite, 52
Ore-formations, 232; origin of, 264; prospecting for, 324, 328
Ores, as clastic formations, 236; as precipitates from aqueous solution, 235; in bedded rocks, 234; in igneous rocks, 59, 233; in lodes, etc., 239; in metamorphic rocks, 238, 256; prospecting for, 324, 328; quasi-bedded, 255
Organically-derived rocks, 74
Original minerals, 38
Orthoclase, 10, 11; -porphyry, 47
Orthogneiss, 87
Orthomagmatic phase of ore-formation, 264
Orthorhombic crystals, 2
Outcrop of strata, 130, 275; affected by faults, 157, 158, 161, 164; concealed, 130, 276, 284, 300; forms of, 285; tracing of, 275; width of, affected by dip, 131, 350; width of, affected by form of surface, 131
Outgoing, of lode, 248
Outlier, 180
Overfolds, 137
Overlap, 185, 288
Oversaturated igneous rocks, 39
Overthrusts, 173, 292
Ovifak, Greenland, 233
Oxford Clay, 117
Oxides, 3; metallic, in igneous rocks, 233

PALINGENESIS, 193
Paragenesis of ores, 250
Paragneiss, 87
Parallel Roads of Glenroy, 307
Parrot coals, 79
Peach, B. N., 177, 292
Peat, 77, 310
Pegmatite, 37, 42, 264; -veins, 204
Pelitic gneiss, 87
Pencatite, 89
Pentland Hills, 49, 51
Perched Blocks, 306
Periclase-marble, 89
Peridote, 21
Peridotite, 58
Perimorphs, 6
Perknite, 58
Perlite, 35
Perlitic structure, 35, 44
Permeation, of fossils, 94
Perthosite, 47
Petrifaction, 94
Petroleum, 81
Phacoids, 227
Phacoliths, 190, 198
Phanerocrystalline, 35
Phemister, J., 47, 292
Phenocrysts, 35, 36
Phlogopite, 17
Phonolite, 40, 55, 56, 209
Phonolitic trachyte, 49
Phosphates, 31, 81
Phosphatic nodules, 82; rocks, 81
Phosphorite, 31
Phyla of animal kingdom as represented by fossils, 98
Phyllite, 86, 226, 228
Picotite, 8
Picrite, 58
Piedmont, ores of, 234
Pigeonite, 20
Pilotaxitic structure, 51
Pipe-clay, 68
Pipes, of ore, 258
Pisolite, 71
Pistacite, 23
Pitch (of fold), 136
Pitchstone, 44, 46
Placers, 236, 261, 266
Plagioclase, 10, 11, 12, 13
Planes of bedding, etc., 109, 110
Plants, geological action of, 357
Plasma, 5
Plateau-basalts, 216
Platinum, 233, 236, 237, 266
Platy lodes, 246
Pleistocene Period, climatic conditions during, 99
Pleonaste, 8
Plutonic igneous rocks, 39, 188
Plutonic metamorphism, 219, 230
Pneumatolytic action, 38, 42, 223, 262, 265
Pockets of ore, 258
Podsols, 377
Polar willow, 99
Porphyrite, 46, 50

Porphyritic structure, 35
Porphyroblastic structure, 85
Post-glacial deposits, 309
Potosi, lodes of, 251
Potstone, 22
Precipitates, ores, 235, 250
Predazzite, 89
Primary depth-zones of ore-deposition, 265
Primary minerals, 37, 38
Prismatic joints, 147, 149, 150, 202
Propylite, 51
Prospecting by Geophysical Methods, 328
Prospecting for ores, 324, 328
Psammitic gneiss, 87
Psephitic gneiss, 87
Pseudoleucite, 55
Pseudomorphs, 7
Pseudotachylyte, 227
Psilomelane, 9, 236
Pulaskite, 47
Pumice, 36
Pyrenees, 222, 300
Pyrite, 28; nodules of, 123, 234
Pyrobitumen, 80
Pyroclastic rocks, 59, 215
Pyrolusite, 9, 236
Pyrope, 24
Pyroxene, 19, 20; -gneiss, 87, 231; -granulite, 89, 231
Pyroxenite, 58
Pyrrhotite, 28, 233, 234, 250

QUAQUAVERSAL folds, 134
Quartz, 3; -basalt, 54; -diorite, 45; -dolerite, 53; -gabbro, 52; in clays, 68, 122; in crystalline igneous rocks, 38, 39, 40; in metamorphic rocks, 85-88; in sands and sandstones, 65, 66; -microdiorite, 46; -porphyrite, 46; -porphyry, 43, 204, 209; -trachyte, 49; varieties of, 5; weathering of, 6
Quartzite, 88, 218; soils derived from, 367
Quartzose granulite, soils derived from, 367
Quasi-bedded ores, 255
Quicksilver formations, 251, 262, 263

RADIOLARIAN chert, 73, 76; earth, 76; jasper, 76
Rain, action of, 355; -prints, 119; -wash, 63
Raised beaches, 309
Rand gold-field, 260
Rattle-stones, 122
Read, H. H., 222
Recumbent folds, 139, 174
Red soils, 369
Reefs, 249, 255
Regional metamorphism, 219, 296
Regression, 186
Re-opening of lodes, 247
Reservoirs, 336
Resorption of minerals, 36
Reversed faults, 168, 173, 292, 298
Rhine Valley, 48, 179, 375
Rhomb-porphyry, 47
Rhyodacite, 45
Rhyolite, 40, 43, 126; soils derived from, 365; -tuff, 60
Rhyolitic obsidian, 44; pitchstone, 44
Richey, J. E., 200, 205
Ridge-faults, 165
Riebeckite, 19; -syenite, 47
Riesengebirge, 238
Rift or grain of rocks, 152
Rill-marks, 119
Ring-dykes, 190, 204, 205, 206
Ring-ores, 248
Ripple-marks, 117, 118
Rivers, as sources of water-supply, 337; older than hill-ranges traversed by them, 178
Roches moutonnées, 305
Rock-beds, formation of, 105
Rock-crystal, 5
Rock, definition of, 33
Rock-disintegration, 354
Rock-flour, 303
Rock-forming minerals, 1
Rock-phosphate, 82
Rock-rubble, 63, 69
Rock-salt, 27, 72
Rocks, 33; concretionary, 124; crystalline igneous, 34; derivative, 61; fossiliferous, 92; fragmental igneous, 59; metamorphic, 83
Rock-sheets, translated, 174, 175, 176, 177
Roman Camp Hill, 182
Rosenbusch, H., 221
Rubicelle, 8
Ruby, 9; spinel-, 8; balas-, 8
Russia, ores of, 233, 237, 238, 263; undisturbed Palæozoic strata in, 108
Rutile, 8, 85

SADDLE-REEFS, 255, 256
St Kilda, 207
Salband, 252
Sand-dunes, 64, 375

Sandstone, 66, 95; columnar, 149; concretionary, 124; -dykes, 216
Sand, volcanic, 59
Sanidine, 11, 48, 55
Sapphire, 9
Sarawak, ores of, 263
Sardonyx, 6
Sarsen-stones, 363
Satin-spar, 30
Saturated igneous rocks, 39
Saussurite, 12; -gabbro, 52
Schillerisation, 51
Schistose-grit, 86
Schistose structure, 83
Schists, 85, 86, 87; fossils in, 96; joints in, 149; ores in, 238. *See also* Metamorphism, 218-230
Schorl, 25; -rock, 42
Schuppen structure, 176
Scoriæ, 59
Scree-breccia, 63
Screens, 205
Seam, 109
Secondary enrichment of lodes, 250; zone of, 266
Secondary minerals, 38, 39
Secondary ore-deposits, 265
Secretionary structures, 125
Sections, horizontal or profile, 315; vertical, 319
Sedentary soils, 361
Sedimentary rocks, 65
Selenite, 30
Semi-opal, 6
Sepiolite, 22
Septaria, 122
Sericite, 17, 228: -schist, 85, 229
Serpentine, 23, 58, 218; soils derived from, 366
Sewage-fields, dangers from, 352
Sgurr Ruadh, 177
Shale, 68; alum-, 68; arenaceous-, 68; carbonaceous-, 68; oil-, 80
Shear-structure, 90
Sheeted zones, 240
Sheets, intrusive. *See* Sills
Shell-marl, 76
Shelly limestone, 76
Shield-volcanoes, 216
Shode-stones, 327
Shoots, 246
Siderite, 29, 238
Sidlaw Hills, 51, 215
Sierra Nevada, 45
Signs used on geological maps, 275
Silicates, 9
Siliceous concretions, 121
Siliceous rocks, 76
Siliceous sinter, 6, 72
Sillimanite, 26; -gneiss, 221, 229; -zone, 228
Sills, 190, 194, 195, 293
Silver, 232, 233, 251, 259, 262, 263
Simple lodes, 240
Simple types of mountain structure, 141, 142
Skeleton crystals, 35
Skye, 199, 207
Slates, 85, 86, 221
Slaty cleavage, 84, 225, 295
Slickensided stones in lodes, 246, 252
Slickensides, 149, 156, 169, 304
Slide, 175
Slieve Gullion, 207
Smaragdite, 19
Snake River, 215
Soapstone, 22
Soda-amphiboles, 19
Sodalite, 14; -phonolite, 56; -syenite, 55; -trachyte, 49
Soil-cap, 360
Soil-deterioration, 378
Soil-erosion, 378
Soil-formation, 376
Soils, 63, 276, 354; mature and immature, 377; surveying of, 276
Solfataric action, 328. *See also* Pneumatolytic action
Sollas, H. B. C., 169
Solutions, siliceous, 4
South America, 82
South Australia, 80
Spathic iron-ore, 73
Specific gravity of minerals, 2
Specular iron, 7
Spessartite, 50
Sphærosiderite, 29; nodules of, 123
Sphene, 25
Spherulitic structure, 35, 43, 44, 46
Spinel, 8, 221, 222
Sponge-chert, 77
Spotted-slate, 86, 221
Springs in bedded rocks, 338, 339; in igneous rocks and schists, 341; shallow and deep-seated, 345; use of, in field geology, 281
Sprudelstein, 75
Stalactites, 70
Stalagmites, 70
Staurolite, 26, 227; -kyanite-gneiss, 229; -mica-schist, 85; -zone, 228
Steam coal, 78

Steatite, 22
Step-faults, 165
Steppes, fauna of, 376
Stilbite, 27
Stocks, 190, 192
Stockworks, 253, 259
Stoneless clay, 373
Stoping, magmatic, 193
Stoss-seite, 305
Strata, contemporaneity of strongly contrasted, 116; grouping of, 114; measurement of, 286; thinning and thickening of, 112, 287
Stratification, 108, 110, 113
Stratified rocks, 61
Stratum, 109
Streak of minerals, 2
Stress minerals, 227
Striæ, glacial, 304, 305
Striated-pavements, 302
Strike, 132; -faults, 158; -joints, 146
Strike-slip fault, 169
Structural geology, 105; economic aspects of, 321, 335
Subaërial rocks, 62
Subhedral (hypidiomorphic) minerals, 35
Subjacent masses, 190
Subsequent eruptive rocks, 188
Subsoil, 63, 276, 354, 362
Succession of minerals in lodes, 250
Suess, E., 169
Sulphates, 30
Sulphide ores, 234
Sulphides, 28
Sun-cracks, 119
Superficial accumulations, 299
Surface-creep, 129
Surface-markings, 117
Surface-wash, 300
Surveying, by aerial photography, 320; geological, 268
Sutherland, 47, 55
Swarms, dyke, 199
Sweden, ores of, 233, 234, 238; varve-clays of, 116
Syenite, 40, 46, 47, 148; micro-, 47
Syenitic mica-trap, 48
Symbols used on geological maps, 275
Symmetrical lodes, 247
Synclinal valleys, 340
Synclines, 135
Synclinorium, 140
Syngenetic ores, 232
Systems of lodes, 242
TABLE of British Fossiliferous Strata, 379
Tachylyte, 54
Talc, 22; -schist, 86, 230
Tear-fault, 169
Tectonic geology, 105
Temperature, underground, 107, 145
Tephrite, 57
Terminal curvature, 129, 130
Terra rossa, 64, 370
Terrestrial movements, evidence of, 103
Tertiary deposits, 299
Teschenite, 56
Tetragonal crystals, 2
Theralite, 40, 56
Thermal metamorphism, 219
Thickening and thinning of strata, 112, 287
Tholeiite, 53
Thomsonite, 27
Throw, of faults, 154
Thrust-planes, 168, 174, 298
Till. *See* Boulder-clay
Tilley, C. E., 228
Tillite, 69
Tinguaite, 56
Tin-ore veins, 223, 252, 265
Titanaugite, 20
Titanite, 25
Tonalite, 45
Topographical maps, 272
Torbanite, 80
Tourmaline, 25, 42, 223
Trachy-andesite, 49; -basalt, 49
Trachyte, 40, 48
Transcurrent faults, 168
Transgression, 186
Translated or travelled rock-sheets, 174, 175, 177
Transported detritus in stream courses, 283; soils, 361, 370
Transvaal, gold of, 260
Transverse lodes, 242
Transverse thrusts, 169, 177
Traprain Law, 198
Travelled soils, 277, 361, 370
Travertine, 70
Trees in peat, 310
Tremolite, 18, 222, 229; -schist, 87, 230
Triclinic crystals, 2
Trigonal crystals, 2
Tripoli-powder, 77
Troctolite, 52
Trondhjemite, 45
Trough-faults, 165
Tschernyscheff, T., 264
Tufa, calcareous, 70, 93; of La Celle, 99

Tuff, volcanic, 60, 96; concretions in, 125
Tundra, 378
Tunnels, construction of, 332
Turgite, 7
Twinning of feldspars, 10, 11
Type-fossils, 104

UNCONFORMITY, 182, 287
Underground water, 338
Underlie (hade) of lodes, 239
Undersaturated igneous rocks, 39
Unilateral compression, 141
United States of America, ores in, 238, 259
Upthrows or upcasts, 155
Ural Mountains, ores of, 233, 237
Uralite, 18
Utah, ores of, 259, 263

VARIOLITE, 54
Variolitic structure, 53
Varve-clays, 116
Vegetable soil, 362
Vegetation, an index to soils, 279
Veins (eruptive), 199, 203, 204
Veins. *See* Lodes
Veinstone or veinstuff, 246
Vertical folds, 134
Vertical sections, 319
Vesicular structure, 36
Vesuvius, 57
Victoria (Australia), placers of, 237
Vitrain, 78
Vitreous rocks, 35
Vogesite, 48
Vogt, J. H. L., 223, 251, 262
Vogt, T., 228
Volcanic agglomerate, 60
Volcanic ash, 59
Volcanic bombs, 59
Volcanic breccia, 60
Volcanic stage of consolidation, 36
Volcanic tuff, 60, 96
Vosges, 221
Vughs, 247, 248

WAD, 9, 236
Walls of lodes, 252
Water-level, 338
Water-supply, 335
Water-table, 338
Wave-marks, 118
Wealden, ores of, 236
Weathering of rocks, 62, 64, 150, 152, 358
Wells, 345
Western Scotland, basalts of, 216
"White trap," 53, 197
Wind, geological action of, 355
Witwatersrand gold-field, 260
Wolframite, 250, 265
Wollastonite-marble, 89
Wrench-fault, 169
Wyoming, U.S.A., 57

XENOLITHS, 42, 192, 193, 222
Xenomorphic (anhedral), 35; -granular, 37

YELLOWSTONE NATIONAL PARK, 44
Young, R. B., 261

ZEOLITES, 26
Zinc-ore, 250, 252, 256, 258, 262, 265
Zircon, 24
Zoisite, 24, 222, 229
Zones of progressive metamorphism, 228

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